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FATIGUE ENDURANCE TESTING OF ION IMPLANTED ROLLER BEARINGS.(U)

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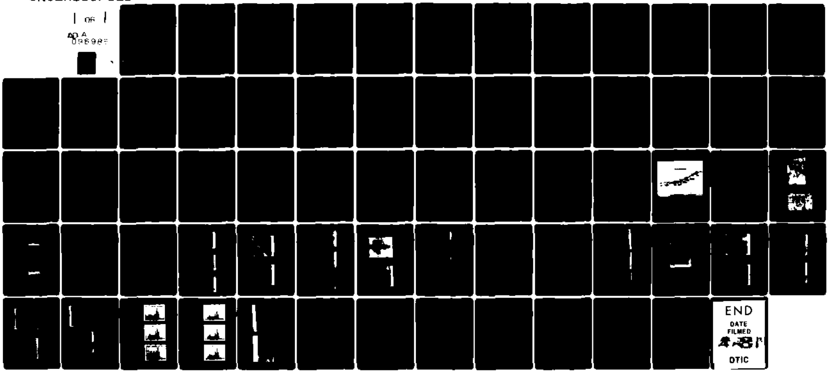

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FATIGUE ENDURANCE TESTING OF ION IMPLANTED ROLLER BEARING

TRW BEARINGS DIVISION
RESEARCH AND DEVELOPMENT LABORATORIES
JAMESTOWN, NEW YORK 14701

FINAL REPORT FOR PERIOD DECEMBER 1978 - OCTOBER 1980

NAVAL AIR PROPULSION CENTER
1440 PARKWAY AVENUE
TRENTON, NEW JERSEY 08628

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Thirty 40-mm bore roller bearings from a single lot were divided into three groups of ten each. One group received chromium ion implantation, a second group received chromium plus phosphorus ion implantation, and the third group was untreated. The bearings were then subjected to fatigue endurance testing and the resulting data analyzed by use of the Weibull Distribution. No significant differences were found between endurance lives of the three groups. Failure mechanisms appeared identical in all bearings.

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FOREWORD

This report describes the work performed by the TRW Bearings Division for the Naval Air Propulsion Center, Trenton, New Jersey under U.S. Navy Contract N00140-79-C-0323. The work described herein was conducted from December 1978 to October 1980.

The Government technical monitors were Daniel Popgoshev and Raymond Valori of the Naval Air Propulsion Center.

The program was conducted at TRW Bearings Division under the direction of Anthony T. Galbato and Harold E. Munson.

Appreciation is extended to James Hirvonen and Graham Hubler of the Naval Research Laboratory, Washington, D.C. for their efforts in designing the ion implantation fixtures and in conducting the ion implantation on the test bearings.

A

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INTRODUCTION

Ion implantation as a means of alloying the load bearing surfaces of gears and rolling element bearings used in Navy and aircraft propulsion systems, has the potential for solving costly problems relating to corrosion and premature surface failures.

Ion implantation is a process by which virtually any element can be injected into the near-surface region of any solid by means of a beam of high-velocity ions (usually tens to hundreds of keV in energy) striking a target mounted in a vacuum chamber. The bombarding ions lose energy in collisions with substrate atoms and come to a stop at depths of tens to thousands of angstroms in the host material. The major advantages of ion implantation over coatings and other methods of surface treatments are:

a. No change in dimensions or surface character which allows the implantation of existing bearings without further processing,

b. None of the interface bonding problems associated with coatings,

c. Material bulk properties remain the same,

d. Choice of alloying element is not limited by solid solubility or diffusion parameters.

Accordingly, ion implantation offers an attractive method of achieving corrosion resistance and improved tribological characteristics.

Consequently the Naval Air Propulsion Center (NAPC) has established and is managing a program to investigate the use of ion implantation for:

a. Producing corrosion resistant alloys on M-50 steel bearing surfaces,

b. Improving the tribological characteristics (wear, scoring, etc.) of bearing surfaces.

Rolling contact fatigue element tests conducted at NAPC have indicated that the ion implantation process is not deleterious to the fatigue life of the host material. The purpose of the program described herein was to carry the testing one step further and determine whether the fatigue life of full scale rolling element bearings is affected by the implantation of ion species which show the greatest improvements in the corrosion resistance of the substrate material.

PROGRAM OUTLINE

TRW Bearings Division fabricated thirty-four 40-mm bore roller bearings as a single lot from double vacuum melted (VIM-VAR) AISI M-50 tool steel. The original intent was to subject fifteen of the bearings to ion implantation while keeping fifteen others as a reference group. The other four bearings were for metallurgical or other destructive analysis. Before implantation was accomplished the program was modified to incorporate two different implantation species; groups of ten bearings each received the two different ion implantations, leaving ten bearings as a reference lot.

Races, raceway sidewalls and rollers were implanted by the Naval Research Laboratory in Washington, D.C. Components for ten bearings were implanted with chromium ions while those for the second group of ten bearings received phosphorus in addition to the chromium. An additional set of races was implanted with chromium ions and several extra rollers received each treatment. Components were returned to TRW Bearings Division where they were examined for comparison with pre-implantation characteristics, then assembled into bearings. The twenty ion implanted bearings and ten standard bearings were then subjected to fatigue endurance testing to determine if ion implantation affected bearing life. Following the test, bearings were examined for cause of failure and for any characteristics which might indicate a difference in performance between the three groups.

BEARINGS

All bearings in this program were MRC R108KD7 roller bearings. They had the following characteristics:

TOLERANCES	- RBEC-5
BORE	- 40-mm, 1.5748 inch, nominal
O.D.	- 68-mm, 2.6772 inch, nominal
WIDTH	- 15-mm, 0.5906 inch, nominal
CONSTRUCTION	- Double flanged inner ring, Single flanged outer ring
RING MATERIAL	- AISI M-50, produced by VIM-VAR process
ROLLER MATERIAL	- AISI M-50, produced by VIM-VAR process
CAGE MATERIAL	- Silicon-Iron-Bronze, silver plated 0.0005-0.0020 inch thick per AMS 2412
ROLLER DESIGN	- 7-mm dia. x 7-mm long with modified crown
CAGE CONSTRUCTION	- 18 roller pockets, inner ring guided
INTERNAL CLEARANCE	- 0.0015-0.0020 inch

Figure 1 is a drawing of this bearing.

THE IMPLANTATION PROCESS

Ion implantation is not a coating technique. Implantation consists of forcibly injecting selected elemental ion species beneath the surface of materials by means of a high-energy ion beam from an accelerator (usually at tens to hundreds of kilovolts). This injection process produces an intimate alloy of the implanted and host elements without producing a sharp interface characteristic of most coatings and hence avoids the related adhesion problems.

The resultant depth distribution and alloy composition depend on the energy and atomic number of the projectile as well as on the atomic number of the host. Typically, depths of 0.01 to 1.0 micrometers are achievable with concentrations of up to 50 atomic percent. It should be stressed that ion implantation is not a thermodynamical equilibrium process and that metastable alloys can be formed without regard for the conventional considerations of solid solubility and diffusivity; since any elemental species can be implanted into any other material. Heating of the implanted alloy to sufficiently high temperatures will, of course, ensure equilibrium conditions, but several durable metastable (or amorphous) phases with potentially interesting physical properties have been formed by implantation. Figure 2 summarizes many of these factors pertaining to ion implantation for materials modification. The ability to control and reproduce the ion beam parameters listed in Figure 2 is especially important to its large scale commercial usage for implanting (doping) semiconductor wafers with high reproducibility (typically less than 3% dose difference on different wafers or between different points on a single wafer).

Figure 3 shows a schematic diagram of a typical research-type ion implantation system. As depicted, atoms are ionized in an ion source, accelerated to the desired energy, analyzed according to mass by a magnet to select the desired species, and then electrostatically raster scanned over the target to ensure dose uniformity of the implantation. The implanted dose (in terms of impurity atoms per unit volume) is obtained from the ion beam charge, the implanted target area, and the implanted species depth distribution.

ION IMPLANTATION

Naval Research Laboratory personnel reported the following relative to the ion implantation process on the bearings in this program:

BEARING SERIAL NUMBER	ION	FLUENCE (ions/cm^2)	ENERGY (keV)	APPROX. WT. % AT SURFACE
R1-R10	Chromium	$2x10^{17}$	150	15.4
	Phosphorus	$1x10^{17}$	40	20
R11-R18, R20, R38, R39	Chromium	$2x10^{17}$	150	19

Temperatures which developed on components during the implantation process:

	NORMAL	*MAXIMUM**
INNER RACES	400°F	550°F**
OUTER RACES	500°F	640°F
ROLLERS	390°F	650°F

* Maximum values were reached by some components for short periods of time.

** The temperature of the inner ring of S/N R17 exceeded 1000°F during implantation.

The rings of S/N R17 were not used for endurance testing but were reserved for stress analysis by X-Ray Diffraction.

TEST EQUIPMENT

Bearings were tested in a battery of four identical test machines. A test machine is shown schematically in Figure 4. Each machine ran four bearings at a time under the following conditions:

SPEED	-	7000 RPM
LOAD	-	2860 pounds radial
LUBRICANT	-	PVO STD. 6530 (MIL-L-23699)
OIL FLOW	-	One quart per minute per bearing by jet
TEMPERATURE	-	$200^{\circ}F$ - $210^{\circ}F$ oil in

Lubricating oil was recirculated and was pumped through a 10 micron (nominal) filter before entering bearings.

An automatic shut-off device based on a chip detector was installed in the oil-out flow of each machine.

Machines were loaded hydraulically by a dynamic pumping system with a precise pressure regulator on each machine.

Each bearing was installed in the test machine with the flanged side of the outer ring oriented as shown in Figure 4 to provide axial stability to a test set-up. Shaft spacers and the central outer ring spacers were dimensioned to provide an axial looseness of 0.010 to 0.015 inch.

Oil temperature was maintained by electric immersion heaters in the oil sump, controlled by an automatic thermocouple-governed controller.

Figures 5 and 6 are photographs of test machines.

TEST PROCEDURE

Each bearing was assembled so that serial numbers of inner ring, outer ring, and cage were on the same side.

Bearings in a particular machine were selected to have the same radial clearance, if possible. It was never necessary to vary radial clearances of bearings within a machine by more than 0.0002 inch. When a failure occurred, all bearings were removed from the rig and arbor; unfailed bearings were reinstalled in their original positions along with a replacement bearing. When a test machine was removed from service, the unfailed bearing was installed in a different machine in the same position.

After a four-bearing spindle had been assembled and installed in a machine, lubricating oil was turned on and the spindle was permitted to sit stationary until temperatures had stabilized. Then the load was applied and the drive motor was started.

Each machine was set-up initially with bearings from all three groups. Typically, a machine could have one chromium implanted bearing, two chromium plus phosphorus implanted bearings, and a reference bearing. Test bearings were further distributed among the different machines so that bearings from each group were spread across all four test positions. As a bearing failed and was replaced, it was general practice to install a bearing from a different group. It had been anticipated that one group might have significantly longer life than others so that near the end of the test only that group would be running; this situation did not develop.

BEARING MEASUREMENT

Following fabrication, each bearing was checked in TRW Bearings Division's Quality Assurance Department for the following parameters:

1. Inner ring bore
2. Outer ring O.D.
3. Diametral clearance
4. Width of rings
5. Width of inner raceway
6. Hardness inner ring
7. Hardness outer ring
8. Surface finish inner race
9. Surface finish outer race
10. Surface finish inner ring lands

Table 1 lists these data, along with measurements after ion implanation, on the twenty bearings which were so subjected.

All rollers were measured for O.D. and length. Sample rollers were checked for:

1. Surface finish
2. Flat length of cylindrical section
3. Crown drop
4. Corner break-out
5. Crown runout
6. Corner runout
7. Hardness
8. Roundness

Table 2 lists these measurements.

One set of rings and one roller were examined by Scanning Electron Microscopy (SEM) for surface characterization. Outer race examination was performed on a replica of the surface.

After ion implantation, measurements of rings, as noted, were repeated with the exception of width. Sample rollers were measured for diameter, roundness, surface finish and hardness. One set of rings plus a roller from each ion implanted group was examined by SEM for surface characteristics. There was no change in dimensional or characteristic measurements.

Following test, the ion implanted components which had been subjected to SEM before test were re-examined by the same means for changes in surface texture. A number of additional rollers and inner rings were likewise examined by SEM in an attempt to pinpoint failure mechanisms.

The following sample rollers were examined by Energy Dispersive X-Ray (EDXR) analysis to evaluate the near-surface chemistry:

1. New - not ion implanted
2. New - chromium implanted
3. New - chromium plus phosphorus implanted
4. Tested - chromium implanted
5. Tested - chromium plus phosphorus implanted

Two additional bearings, S/N R17 (chromium implanted races) and S/N R37 (a reference bearing), plus sample implanted and unimplanted rollers, were tested for residual stress by X-Ray Diffraction Analysis. Values were measured at the surface and at various depths up to 0.007 inch, with stock removal by chemical polishing to permit measurement at locations below the original surface. Table 3 lists the data. Note that bearing S/N R17 was the one whose rings exceeded 1000°F during implantation, as stated earlier.

Ion implanted components were examined visually upon return from Naval Research Laboratory. Some rings were somewhat discolored on the faces, with a light brown stain. The inner rings of S/N R3 and R4 were most noticeably discolored. Naval Research Laboratory personnel indicated that this marking came from contact with a heat sink used during implantation.

Many of the rollers showed bands, like shadows, running axially across the surface. Occasionally the discoloration was wedge shaped (see Figure 7). Measurements of roller diameter of sample rollers, with resolution of a few microinches showed no variation corresponding to the coloration. Figure 8 is a trace of the O.D. of a roller which had distinct markings. Surface finish measurements indicate a difference of approximately 0.5 microinch between dark and shiny areas with the dark areas having the higher reading. Naval Research Laboratory personnel identified the roller discoloration as aluminum oxide of an unknown source. Aluminum oxide may be the result of the finish grinding and lapping operations (ref. 1).

Following test, the bands could still be seen on some rollers. Where bands could be identified on failed rollers there appeared to be no correlation with failure location.

A tested roller exposed to EDXR chemical analysis showed aluminum still present at the surface.

TEST RESULTS

A total of thirty-two (32) MRC R108KD7 roller bearings were subjected to fatigue endurance testing under previously described conditions. These bearings were made up of the following groups:

10 bearings, S/N R1 through R10	-	Chromium plus phosphorus implanted
10 bearings S/N R11 through R16, R18, R20, R38, R39	-	Chromium implanted
10 bearings S/N R22, R23, R24, R26 R28, R29, R30, R31, R32, R36	-	Reference Bearings
2 bearings S/N R33 and R34	-	Same as Reference bearings except that rollers were from a different lot

Endurance life data are summarized in Table 4. These data are plotted on a Weibull Chart, Figure 9. The endurance life of S/N R38, the only failure involving any component except rollers, is omitted from the chart. The chromium plus phosphorus implanted bearings ran 90% and the chromium implanted bearings ran 110% as long as the reference bearings at the L-10 level. These differences are not statistically significant. The calculated 90% confidence bands (ref. 2) based on the test data from the Reference Lot are superimposed on the Weibull Chart and effectively encompass all datum points.

There are two unexpected aspects of this testing:

1. Overall lives were shorter than expected
2. All failures involved rollers

The calculated life for this bearing by the AFBMA method neglecting material and lubrication factors, but considering the geometry of the crowned portion of the rollers, is 15 hours. Life adjustments are:

D	(material factor) for M-50	= 2
E	(melting practice factor) for Vacuum Arc Remelt	= 3
F	(lubrication factor)	= .25

There is considerable opinion that "E" should be higher than 3 for vacuum induction melt - vacuum arc remelt (VIM-VAR) processed bearing steel but currently no separate value has been established. Using the above factors the calculated L_{10} life for the bearing under these conditions is 2x3x.25x15 = 22.5 hours. Since the L-10 lives obtained in test were 2.3X to 3.2X this value, overall performance was not unreasonable.

In fatigue endurance testing of bearings, the majority of failures usually occur in the inner races. Thus, a distribution of failures which is almost entirely limited to rollers is unusual. There was no apparent difference in failure mechanism between ion implanted rollers and untreated rollers, so the fact that rollers rather than races failed is largely incidental to this program.

However, bearing components have been examined in an attempt to ascertain the cause of failure. Certain facts which relate to the question are:

1. The rollers were slightly softer (0-2 points on the Rockwell C scale) than were the rings;

2. Fatigue spalls appeared to have generally started on the crowned portion of the rollers near the corner;

3. The crowned portion of the rollers adjacent to the corners were frequently burnished and sometimes had microscopic superficial spalls;

4. A few "unfailed" rollers had microscopic spalls in the crowned area at some distance from the corner; some of these were surface initiated but some could not be so defined;

5. When a spalled roller ran for some significant length of time after failure, the spalled area extended length-wise across the roller;

6. If an extensive spall was not rectangular in surface shape it tended to be widest near a corner of a roller;

7. Raceways were generally in good condition with occasional dents.

8. Calculations indicated relatively high stresses at the ends of the rollers, although these stresses were somewhat less than those in the central portion of the rollers.

9. Measurements of spalls showed greater depth in the central flat than near the end, indicating that stress calculations are valid. Typical values of the depth were 0.008 vs. 0.0045 inch.

10. Electron beam microscopy showed superficial spalls starting a few thousandths of an inch from the corner break, resulting from a combination of scuffing (due to skewing) and heavy load.

Rollers tend to wobble or skew as they travel around a race, particularly in an unloaded or lightly loaded condition. In this test each roller was unloaded half of the time, then very heavily loaded as it passed through the stressed zone. Some skewing occurred in these bearings and is evident from a slight "dog bone" wear pattern in the cage pockets. Roller end wear was negligible, however. The surface distress which developed near the ends of many rollers presumably occurred as rollers were forced to make adjustments in direction under heavy load; because of the heavy load the surface distress often manifested itself as microspalling.

It seems likely that a microspall occasionally developed into a full fledged spall. Because of the very heavy load, loss of a small amount of supporting surface caused extremely high stresses to adjacent areas so the spalled area extended rapidly. The fact that races generally did not spall while rollers were failing is probably due to the fact that rollers were softer than rings.

CONTACT STRESSES

Appendix A presents computer print-outs of stresses, deflections, endurance life, etc. relative to the MRC R108KD7 roller bearing operating under the specified conditions. The data in A-1 were based on a roller flat length of 0.0920 inch while the data in A-2 used a flat length of 0.1720 inch. These values were the minimum and maximum values, respectively, for the flat length of the modified crown of the rollers used in this test. The computer program used to calculate bearing performance was Franklin Institute's GENROL, Level 24 (ref. 3). In setting up the input data a mounted radial clearance of 0.0015 inch was used, based on a maximum unmounted clearance of 0.0020 inch modified by a loss of 0.0005 inch due to press fit of the inner ring on the shaft. The computer program divided the effective length of each roller (total length less two corners) into 20 laminae of equal width and calculated the stress on each.

The calculated mean Hertz stress on the central portion of the most heavily loaded roller was approximately 300,000 psi. The calculated Hertz stress on the most outboard laminae was approximately 25,000 to 50,000 psi less than the central area as calculated by the GENROL program indicating that the condition of "edge loading" was being approached.

In a cylindrical roller bearing operating under heavy load, the stressed area of the raceways deflect. At the edges on either side of the loaded area, the change in profile of the raceway tends to produce stress concentrations which are significantly higher than Hertz stress formulas would indicate. The geometry of rollers is modified from true cylinders by "crowning" to provide relief near the ends and thus prevent edge loading. However, edge loading can still occur if the load is heavier and hence raceway deflection is greater than the crowned relief can accommodate. The high stresses produced by edge loading produce fatigue spalls near the ends of the rollers or at the edges of the raceways.

A roller with maximum flat length would be most susceptible to edge loading effects. Failed rollers were checked for length of central flat and location of this flat. All fell within specified tolerances and most were very close to the midpoint of the range.

SURFACE FINISH

Figures 10,11,12,13,and 14 are scanning electron microscope (SEM) photos of selected components at 4700 X magnification. All SEM photographs were taken at Calspan Laboratories, Buffalo, New York. Figures 10 and 11 show segments of the raceway surfaces of S/N R8 as manufactured, after ion implantation, and after running. An attempt was made to take these photos at the same spot based on an index mark on the ring face, but we were unable to locate the exact point on the race each time. Figure 12, and also Figure 13, are SEM photos of replicas of the outer race surface; replication was necessary because the configuration of the outer ring precluded direct examination. Figures 11 and 13 show segments of the raceway surfaces of S/N R18 after ion implantation and after running. S/N 8 and S/N 18 are representative bearings demonstrating the two different ion implantation species involved in this program. Figure 14 shows segments of surfaces of a new roller; a chromium plus phosphorus implanted roller; and the latter roller after test in bearing S/N R8. The new roller is not the same one as is shown in the other sections of Figure 14.

The photographs give some indication of a blending of sharper features of finish by the ion implantation; however, surface finish measurements, as shown in Table 1, do not indicate any significant difference. Following test the SEM photographs show both a peening over of grinding marks and an apparent roughening, but the original finishing marks are still clearly visible.

Measurement of surface finish on sample tested but unfailed parts indicated an increase of inner race values from the 4-5 microinch range to 6-8 microinches. Outer raceway finish values increased from the 3-5 microinch range to 5-6 microinches. Sample roller surfaces measured 3-4 microinches. There was no discernable difference in surface finish performance between implanted bearings and reference bearings.

RESIDUAL STRESS

Table 3 and Figures 15 and 16 present data on residual stresses developed in implanted and reference bearing components. Normal grinding and finishing operations produce relatively high residual compressive stress on the surface of a hardened part. At a short distance below the surface, these stresses decay to essentially a no stress condition but pass through a zone of low tensile stress. Thus, the residual stress patterns of the reference bearing components were quite normal.

The ion implanted parts followed the same general residual stress patterns as the reference parts. It had been suggested that ion implanted components might have higher surface stresses than reference parts because of the energy involved in impinging ions into the surface. Actually, the ion implanted races showed lower stresses at the surface than did the reference bearings, and the stress pattern of the inner race of S/N R17 deviated somewhat in details from the other rings. This particular ring overheated during the implantation process (temperature exceeded 1000^{o}F) and the high temperature probably resulted in some stress relief. Unfortunately this inner race was the only implanted one which was not required for fatigue endurance testing.

Residual stresses were measured by X-Ray Diffraction in the TRW Bearings Division Materials Laboratory. To obtain stress values at points below the original surface, parts were chemically polished to remove stock to the required depth. The measurement by X-Ray Diffraction involves an averaging of values over a depth of approximately 0.00015 inch; therefore the depths listed on Table 3 and on Figures 15 and 16 are the distances from the original surface and the measured stresses include data developed from material slightly deeper than the nominal depths.

FAILURES

All failures except S/N R38 involved spalled rollers. S/N 38 experienced a spalled inner ring at less than half the life of any other failure. This anomalous failure is omitted from the Weibull analysis shown on Figure 9.

Figure 17 shows photographs of typical spalls, occurring in rollers in bearings S/N R6, R11, and R26. These rollers were chromium plus phosphorus ion implanted; chromium ion implanted; and unimplanted, respectively. The three failures appear to have been produced by the same mechanism and to have progressed in the same manner.

In an attempt to determine if the observed roller failure pattern was characteristic of a particular lot of rollers, a second lot of rollers was obtained. This additional lot was made from VIM-VAR M-50 tool steel. Its hardness was the same and rollers could be matched with existing races to meet radial clearance specifications. Crown geometry was somewhat different, as noted in Table 2; this would produce lower stresses on the outboard laminae.

Rollers from the second lot were installed in bearing S/N R33 and R34. Both bearings failed from the same mechanisms and at comparable times as bearings having the original lot of rollers.

Figure 18 shows a spalled roller, in bearing S/N R3, which ran for some period of time after failure initiated. Presumably, failure started on one side, then progressed across the whole effective length of the roller and widened somewhat. This pattern of spall extension is found in representative rollers with both implantation species and in the reference group.

Examination of unfailed rollers shows some scuffing near the corner break. Figure 19 shows SEM views of the corners of a roller from S/N R7. This bearing ran 420 hours without failure. The roller scuffing shown in this roller appears considerably more severe than in most rollers. Back from the corners are areas of very fine pitting.

A more typical condition than the severe scuffing of Figure 19 is microspalling which occurred in many rollers a few thousandths of an inch back from the corner. Figure 20 shows SEM views of areas near the corners of a roller from S/N R16; this is typical of many rollers.

Figures 21 and 22 are SEM photos of inner raceway corners. Since the raceway corners have smaller radii than the roller corners, contact is not made between roller and race within 0.015 inch or more from the side wall. Figure 21, showing the corners of S/N R7, has scuffed areas corresponding to the contact with the scuffed rollers. Figure 22, showing the corners of S/N R8, a bearing which had a spalled roller, has much less pronounced scuffing. Typically, races show much less scuffing, microspalling, or denting damage than do rollers.

SURFACE CHEMISTRY

Figures 23 and 24 are photos of Energy Dispersive X-Ray (EDXR) chemical analyses of the surface of sample rollers involved in this program. Figure 23 provides a comparison of a new roller, an unused chromium ion implanted roller, and a tested roller having chromium ion implantation. Figure 24 is comparable to Figure 23, differing in that the rollers were subjected to chromium plus phosphorus ion implantation.

In all the photos of Figure 23 and 24, the FeK_{β} line is used as reference. This is practically the same height in all cases. The chromium line in the unused implanted rollers can be seen to be higher than the corresponding line in tested rollers, and both are higher than the chromium line in the new roller. M-50 tool steel contains 4% chromium as manufactured; the chromium content of the surface is shown to be enriched by implantation with partial loss of the increase during bearing operation.

M-50 tool steel contains phosphorus as a trace element only. Figure 24 shows a phorphorus line on the implanted rollers, both new and tested, with little difference between the two.

Aluminum is present in M-50 tool steel only as a trace element. In Figure 23, the aluminum line on the tested roller is believed to be related to the aluminum oxide which discolored portions of the surface of many rollers (Figure 7).

METALLURGICAL INSPECTION

Sample inners, outers, and rollers - implanted and unimplanted - were sectioned and subjected to metallurgical inspection near the surface. No difference in microstructure could be observed between implanted and unimplanted parts.

Figure 25 shows a comparison of the microstructure of the inner race of S/N R27, which was not implanted and the outer race of S/N R38, which was subjected to chromium ion implantation. (S/N R38 was run in fatigue test; the area examined here was on the unflanged side adjacent to the raceway).

CONCLUSIONS:

1. Ion implantation of the species and dosage levels evaluated herein were found not to be detrimental to fatigue endurance life.

2. Failure in all cases was due to fatigue spalling. Ion implantation did not effect the characteristics of the fatigue spalling.

3. The ion implantation process does not effect the bulk metallurgy (microstructure) of AISI M-50 steel.

4. The residual stresses on implanted and on unimplanted test specimens are not significantly different.

5. The ion implantation did not effect the dimensions of the test bearings within measurable limits.

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TABLE - 1

MEASUREMENT DATA (inches)

S/N	BORE		O.D.		RADIAL CLEARANCE		WIDTH		
	BEFORE	AFTER	BEFORE	AFTER	BEFORE	AFTER	INNER	OUTER	INNER CHANNEL
R1	1.5747	1.5747	2.67703	2.6770	.0020	.0019	.5901	.5900	.2770
R2	1.5747	1.5747	2.67715	2.67715	.0020	.0020	.5900	.5900	.2770
R3	1.57473	1.57465	2.6771	2.67705	.0019	.0019	.5904	.5900	.2770
R4	1.5747	1.5747	2.6771	2.67705	.0017	.0016	.5899	.5899	.2770
R5	1.57473	1.57467	2.67703	2.67695	.0016	.0015	.5901	.5900	.2768
R6	1.5747	1.57463	2.67713	2.6771	.0020	.0019	.5901	.5899	.2768
R7	1.5747	1.57464	2.67703	2.6770	.0018	.0018	.5904	.5898	.2770
R8	1.57465	1.57465	2.6771	2.6771	.0018	.0017	.5899	.5899	.2770
R9	1.57465	1.5747	2.67705	2.67702	.0020	.0019	.5898	.5898	.2770
R10	1.5747	1.5747	2.6771	2.6771	.0020	.0020	.5900	.5901	.2770
R11	1.57468	1.57463	2.67698	2.67698	.0018	.0017	.5903	.5898	.2770
R12	1.5747	1.5747	2.6771	2.67715	.0020	.0020	.5904	.5898	.2770
R13	1.57465	1.5747	2.6771	2.67707	.0019	.0018	.5898	.5900	.2770
R14	1.5747	1.5747	2.67693	2.6769	.0020	.0019	.5901	.5900	.2770
R15	1.5747	1.57465	2.67715	2.67715	.0017	.0016	.5901	.5898	.2770
R16	1.57473	1.57465	2.6771	2.67705	.0016	.0015	.5901	.5900	.2768
R17	1.5747		2.67695		.0018		.5901	.5899	.2768
R18	1.5747	1.57465	2.67695	2.6770	.0017	.0016	.5901	.5900	.2768
R20	1.57473	1.57465	2.67705	2.67708	.0017	.0016	.5901	.5897	.2770
R22	1.57473		2.6771		.0019		.5899	.5899	.2772
R23	1.5747		2.67715		.0018		.5903	.5899	.2770
R24	1.5747		2.6771		.0018		.5902	.5899	.2770
R26	1.5747		2.67705		.0020		.5902	.5899	.2770
R28	1.5747		2.6771		.0020		.5902	.5899	.2768
R29	1.5747		2.6771		.0019		.5899	.5900	.2770
R30	1.5747		2.6771		.0019		.5901	.5901	.2768
R31	1.57473		2.67715		.0019		.5903	.5900	.2770
R32	1.5747		2.6771		.0019		.5900	.5899	.2770
R33	1.5747		2.6771		.0018		.5900	.5899	.2770
R34	1.57473		2.67708		.0018		.5904	.5901	.2770
R36	1.57468		2.67705		.0019		.5903	.5899	.2770
R38	1.57468	1.5747	2.67715	2.6771	.0018	.0018	.5899	.5899	.2768
R39	1.57465	1.5747	2.67715	2.6771	.0018	.0018	.5903	.5898	.2768

TABLE - 1 Continued

MEASUREMENT DATA

S/N	SURFACE FINISH (microinches) INNER RACE BEFORE	INNER RACE AFTER	OUTER RACE BEFORE	OUTER RACE AFTER	INNER LAND BEFORE	INNER LAND AFTER	HARDNESS (ROCKWELL C) INNER RING BEFORE	INNER RING AFTER	OUTER RING BEFORE	OUTER RING AFTER
R1	5	4	4	3	6	6.5	62.5	63.2	64	63.8
R2	3	3	4	3.5	7	7	62.5	63.5	63	62
R3	4	5	4	4.5	6	7	63	62.8	63	63.2
R4	5	5.5	4	4	6	6	63	63.5	64	63.8
R5	5	6	4	5	6	6	63	63	64	63.8
R6	4	5	4	5	7	6.5	62.5	63.2	63	63
R7	4	4	3	3.5	7	5	62.5	63	64	64
R8	4	4.5	4	4.5	6	6	63	63	64	63
R9	4	4.5	3	3.5	6	6.5	62.5	63	64	63.2
R10	5	5.5	4	3	6	7	62.5	63	64	64.2
R11	5	6	5	5.5	5	6	63	63	63	63.2
R12	6	7	4	3.5	6	6	62.5	63.2	63	63.5
R13	5	5.5	4	5	6	7	63	63.5	64	64
R14	5	4.5	3	3.5	5	6	63	63.2	64	63.5
R15	5	5.5	4	4	6	5.5	63	63	64	63.2
R16	4	4.5	4	3.5	6	5	62.5	63.5	64	63.5
R17	5	-	4	-	6	-	63	-	64	-
R18	5	6	4	4	7	7	62	63	63	63
R20	5	5.5	5	5	6	7	63	63.5	64	63.8
R22	4		4		5		62.5		64	
R23	4		5		6		63		64	
R24	5		4		6		63		64	
R26	5		4		7		63		63	
R28	4		4		5		62.5		64	
R29	5		5		5		63		64	
R30	4		3		6		63		64	
R31	4		4		7		62.5		63	
R32	4		3		6		62.2		64	
R33	5		4		5		62		64	
R34	5		4		6		62		63.8	
R36	4		3		6		62.5		63	
R38	5	5.5	5	5.5	5	5	63	63.5	64	64
R39	5	6	4	4.5	5	6	62.5	63.2	63	64

TABLE - 2

MEASUREMENT DATA

ROLLERS

DIAMETER	- 0.276175	- 0.2762 inch		Before and after implantation
LENGTH	- 0.2756	- 0.2758 inch		Before and after implantation
FLAT LENGTH	- 0.0920	- 0.1720 inch		Specified; sample varied from 0.110 - 0.150 inch
CORNER BREAKOUT	- 0.015	- 0.020 inch		
CROWN DIAMETER	- 30 inches, nominal			
SURFACE FINISH	- 1.5 to 3 microinches, before and after implantation			
HARDNESS	- 61.7 to 62.7 Rockwell C (Sample)			
ROUNDNESS (two point)	- within 0.000010 inch			

Two bearings were assembled with rollers from a different lot of VIM-VAR M-50 rollers and put into test for comparison purposes. These rollers had the following geometry:

DIAMETER	- 0.27605 - 0.276075 inch	
LENGTH	- 0.2754 - 0.2756	inch
FLAT LENGTH	- 0.1280 - 0.1670	inch
CROWN RADIUS	- 15.5 inches, nominal	
HARDNESS	- 61.6 to 62.7 Rockwell C (Sample)	

TABLE - 3

RESIDUAL STRESS MEASUREMENTS (K psi)

	OUTER RACES		INNER RACES		ROLLERS		
DISTANCE BELOW SURFACE (INCH)	S/N R37 REFERENCE	S/N R17 IMPLANTED	S/N R37 REFERENCE	S/N R17 IMPLANTED	NEW	CHROMIUM IMPLANTED	CHROMIUM + PHOSPHORUS IMPLANTED
SURFACE	-106.1	-85.9	-106.5	-76.4	-181.6	-179.1	-148.3
.0002	-49.6	-43.2	-26.4	-29.3	-45.1	-85.9	-65.0
.0004	-	-27.9	-11.2	-8.9	-30.7	-41.6	-29.2
.003	+12.5	+12.5	+18.7	-6.2	+6.4	-	-12.2
.005	+24.2	+17.2	+14.9	+4.1	+0.2	+10.1	+4.3
.007	+21.0	+1.2	+18.2	-3.7	+11.1	+8.4	+3.2

TABLE 4

FATIGUE ENDURANCE LIVES

S/N	GROUP	MACHINE	POSITION	HOURS	STATUS
R1	Cr+P	A-9	3	351.8	No failure
R2	Cr+P	A-9	2	100.1	Spalled Roller
R3	Cr+P	A-10	3	93.0	Spalled Roller
R4	Cr+P	A-11	1	191.4	Spalled Roller
R5	Cr+P	A-11	4	81.7	Spalled Roller
R6	Cr+P	A-12	1	361.2	Spalled Roller
R7	Cr+P	A-11, 12	3	420.4	No Failure
R8	Cr+P	A-12	2	191.7	Spalled Roller
R9	Cr+P	A-12	2	278.4	Spalled Roller
R10	Cr+P	A-9	1	92.6	Spalled Rollers (2)
R11	Cr	A-10, 9	1	150.9	Spalled Roller
R12	Cr	A-9	3	135.1	Spalled Roller
R13	Cr	A-10,9	4	399.3	Spalled Roller
R14	Cr	A-12	3	127.4	Spalled Roller
R15	Cr	A-12	1	306.9	No failure
R16	Cr	A-11	1	132.8	Spalled Roller
R18	Cr	A-12	3	94.4	Spalled Roller
R20	Cr	A-11, 12	4	193.4	Spalled Rollers (2)
R38	Cr	A-11	2	36.2	Spalled Rollers and Inner
R39	Cr	A-10	3	252.2	Spalled Roller
R22	Ref	A-10	1	177.6	Spalled Roller
R23	Ref	A-11	3	76.2	Spalled Roller
R24	Ref	A-12, 10	3	177.9	Spalled Roller
R26	Ref	A-9	4	383.8	Spalled Roller
R28	Ref	A-9	1	394.3	No failure
R29	Ref	A-10	2	296.8	Spalled Roller
R30	Ref	A-11	2	86.9	Spalled Roller
R31	Ref	A-9	2	113.2	Spalled Roller
R32	Ref	A-9	2	221.9	Spalled Roller
R36	Ref	A-12	4	361.4	No failure
R33	Ref*	A-11	2	78.0	Spalled Roller
R34	Ref*	A-10, 12	3	215.9	Spalled Roller

* THESE BEARINGS HAVE ROLLERS FROM A SECOND LOT

MATERIAL:

RINGS: VIM-VAR M-50 TOOL STEEL

ROLLERS: VIM-VAR M-50 TOOL STEEL

CAGE: SILICON-IRON-BRONZE, SILVER PLATED .0005 in. to .0020 in. PER AMS 2412

RBEC 5 TOLERANCES

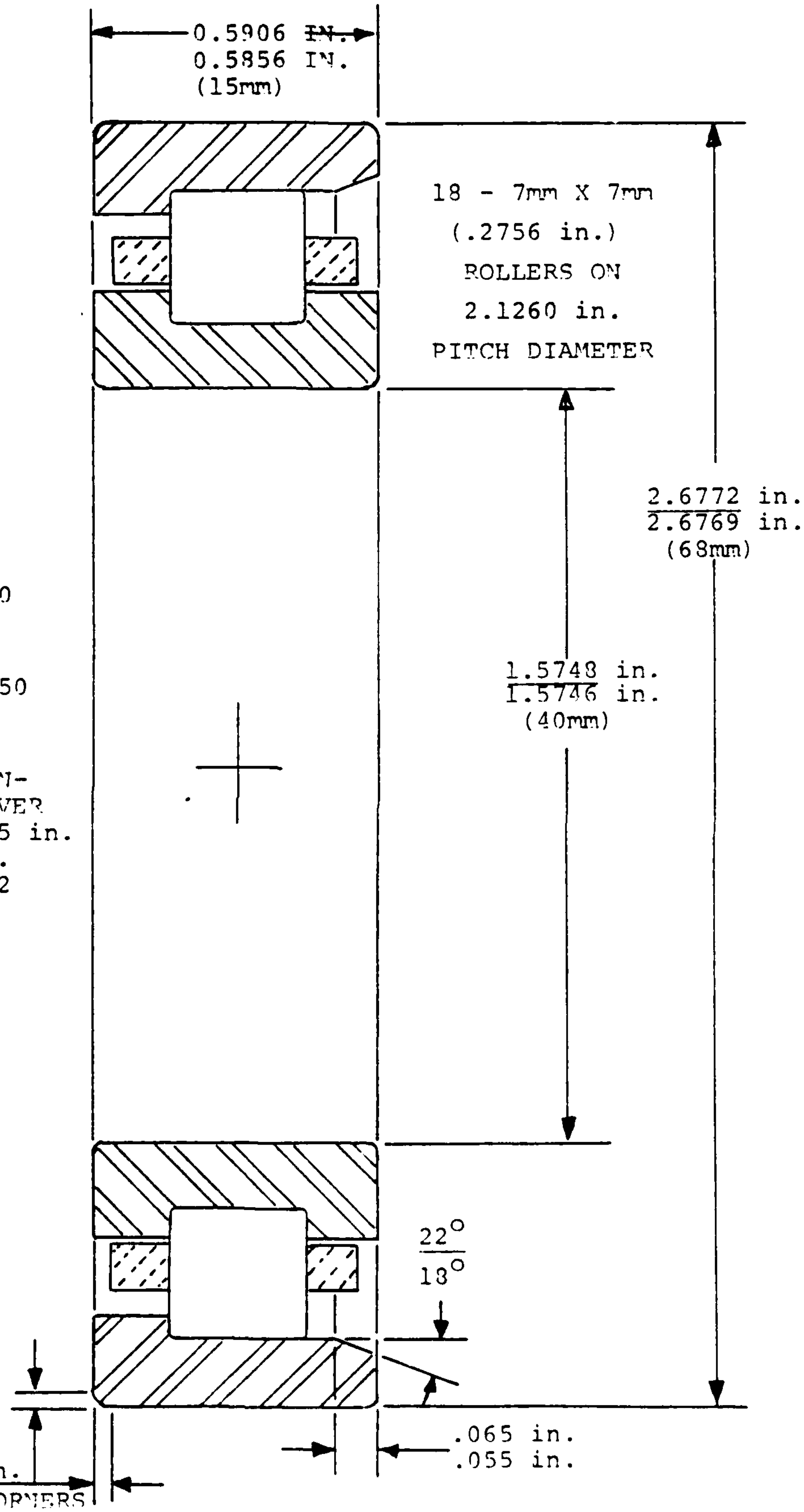
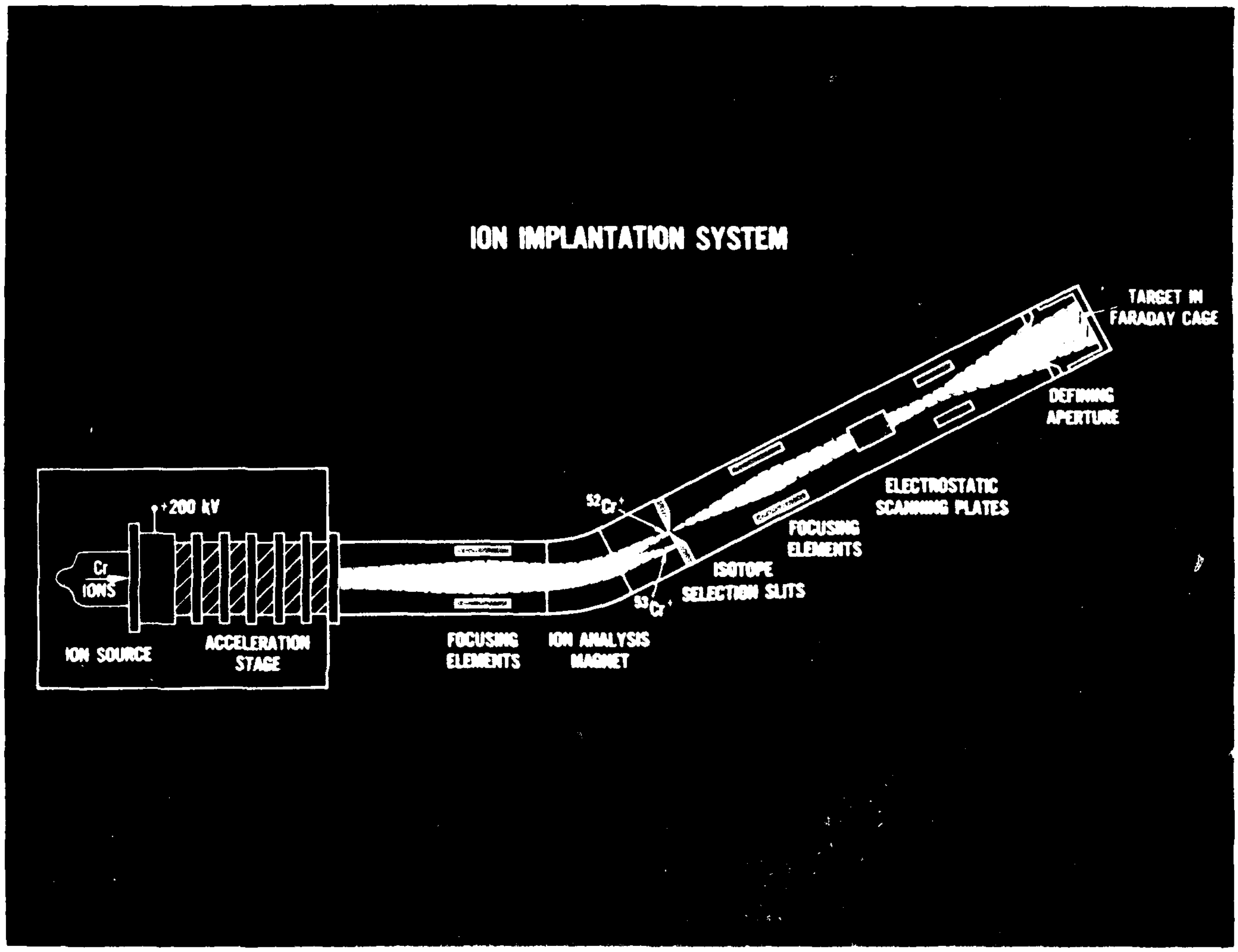


FIGURE 1 - MRC R108KD-7 ROLLER BEARING

ION IMPLANTATION PARAMETERS

IMPLANTED ELEMENTS	-	VIRTUALLY ANY ELEMENT FROM HYDROGEN TO URANIUM CAN BE IMPLANTED.
ION ENERGIES	-	NORMALLY 2 TO 200 KeV. ENERGIES UP TO 5 MeV MAY BE OBTAINED WITH THE VAN DE GRAAFF ACCELERATOR.
ION RANGES	-	VARY WITH ION ENERGY, ION SPECIES AND HOST MATERIAL. RANGES NORMALLY 0.01 μm to 1.0 μm.
RANGE DISTRIBUTION	-	APPROXIMATELY GAUSSIAN. CHOICE OF ENERGIES ALLOW TAILORED DEPTH DISTRIBUTION PROFILES.
CONCENTRATION	-	FROM TRACE AMOUNTS UP TO 50% OR MORE.
HOST MATERIAL	-	ANY SOLID MATERIAL CAN BE IMPLANTED.
SPECIAL EFFECTS	-	SPUTTERING, RADIATION DAMAGE, RADIATION ENHANCED DIFFUSION.

Figure 2 - The effect produced by ion implantation depends on a number of parameters. These parameters, together with typical ranges of values, are shown here.



ION IMPLANTATION SYSTEM
+200 kV
Cr IONS
ION SOURCE
ACCELERATION STAGE
FOCUSING ELEMENTS
ION ANALYSIS MAGNET
$^{52}Cr^+$
$^{53}Cr^+$
ISOTOPE SELECTION SLITS
FOCUSING ELEMENTS
ELECTROSTATIC SCANNING PLATES
DEFINING APERTURE
TARGET IN FARADAY CAGE

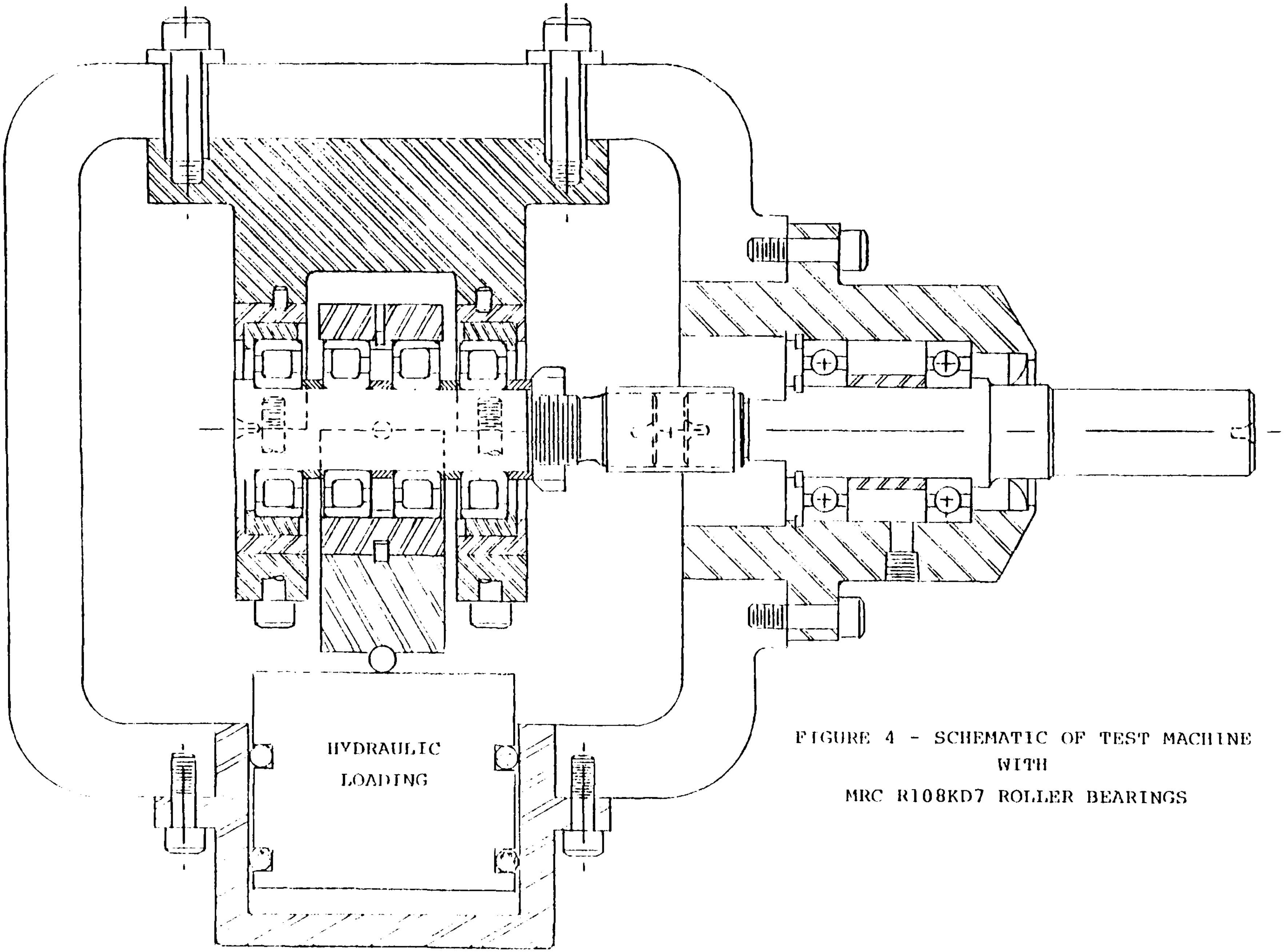


FIGURE 4 - SCHEMATIC OF TEST MACHINE
WITH
MRC R108KD7 ROLLER BEARINGS

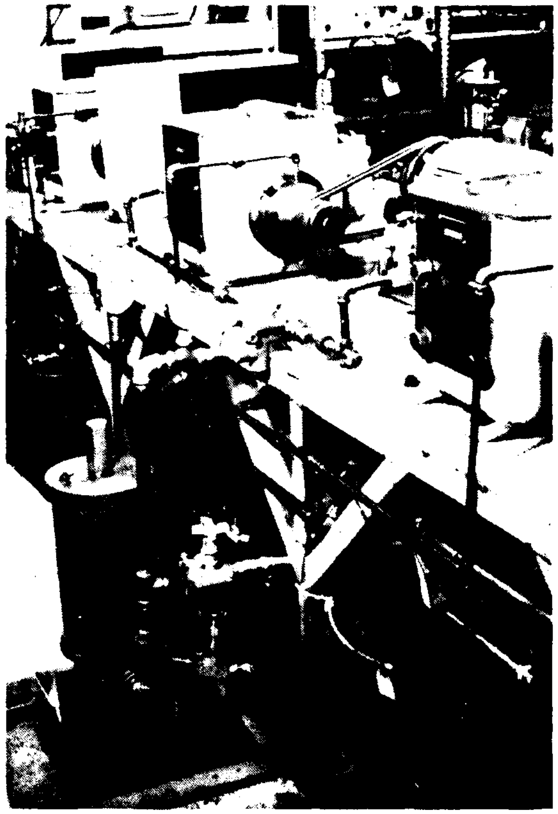


FIGURE 5 - BATTERY OF MACHINES USED FOR FATIGUE ENDURANCE TESTING

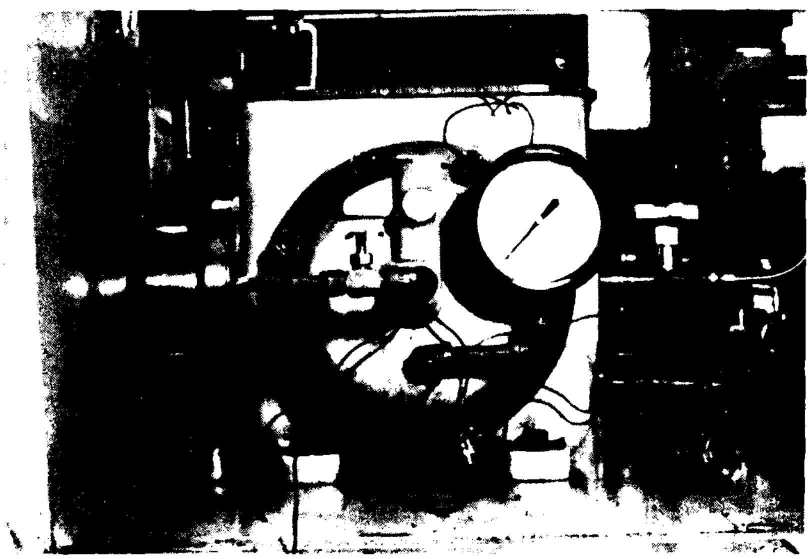


FIGURE 6 - FATIGUE ENDURANCE TEST MACHINE

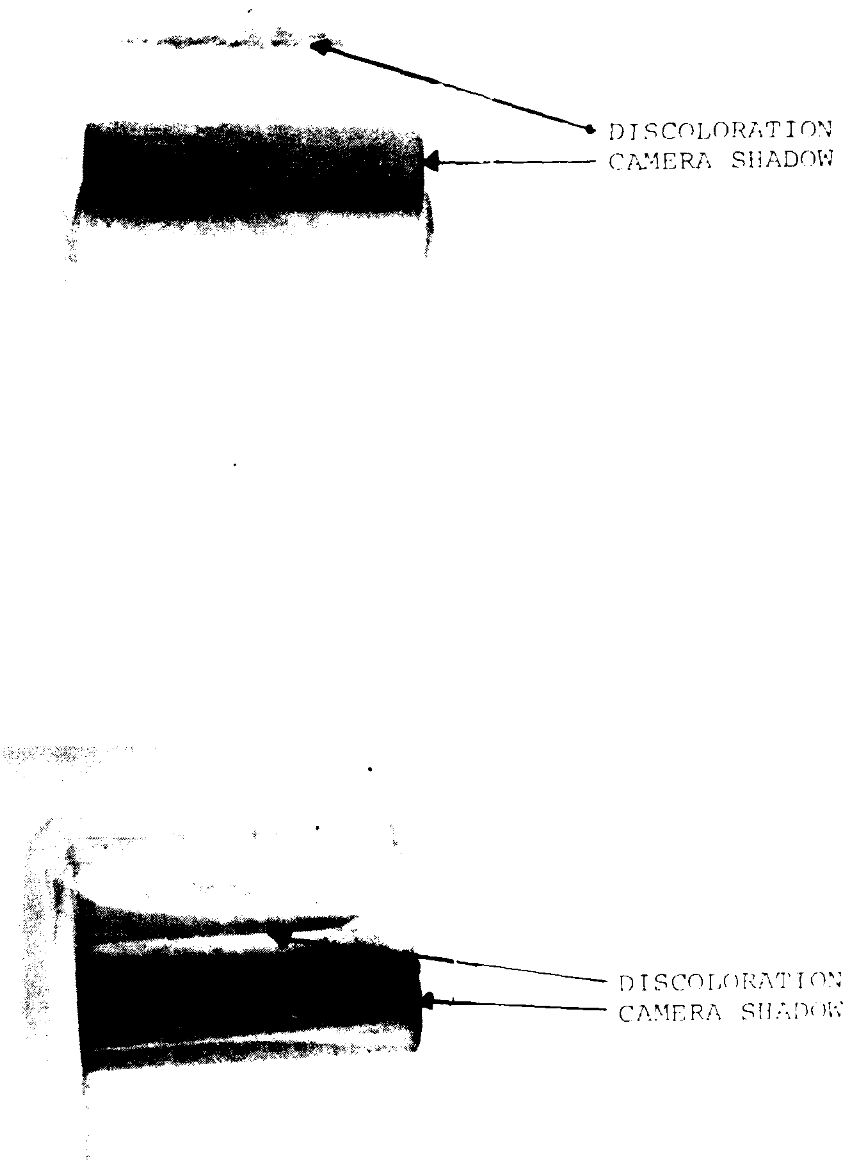


FIGURE 7 - ION IMPLANTED ROLLERS WITH DISCOLORED AREAS

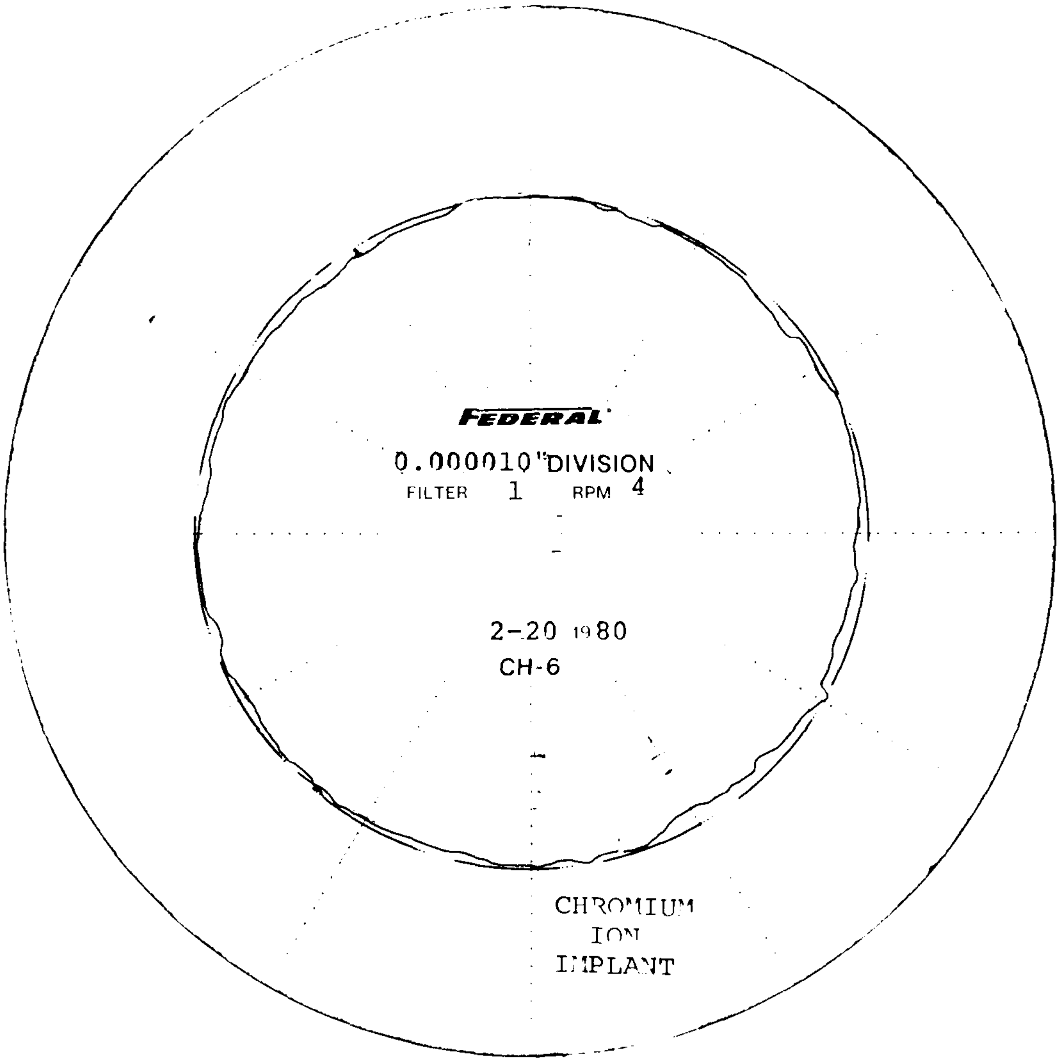
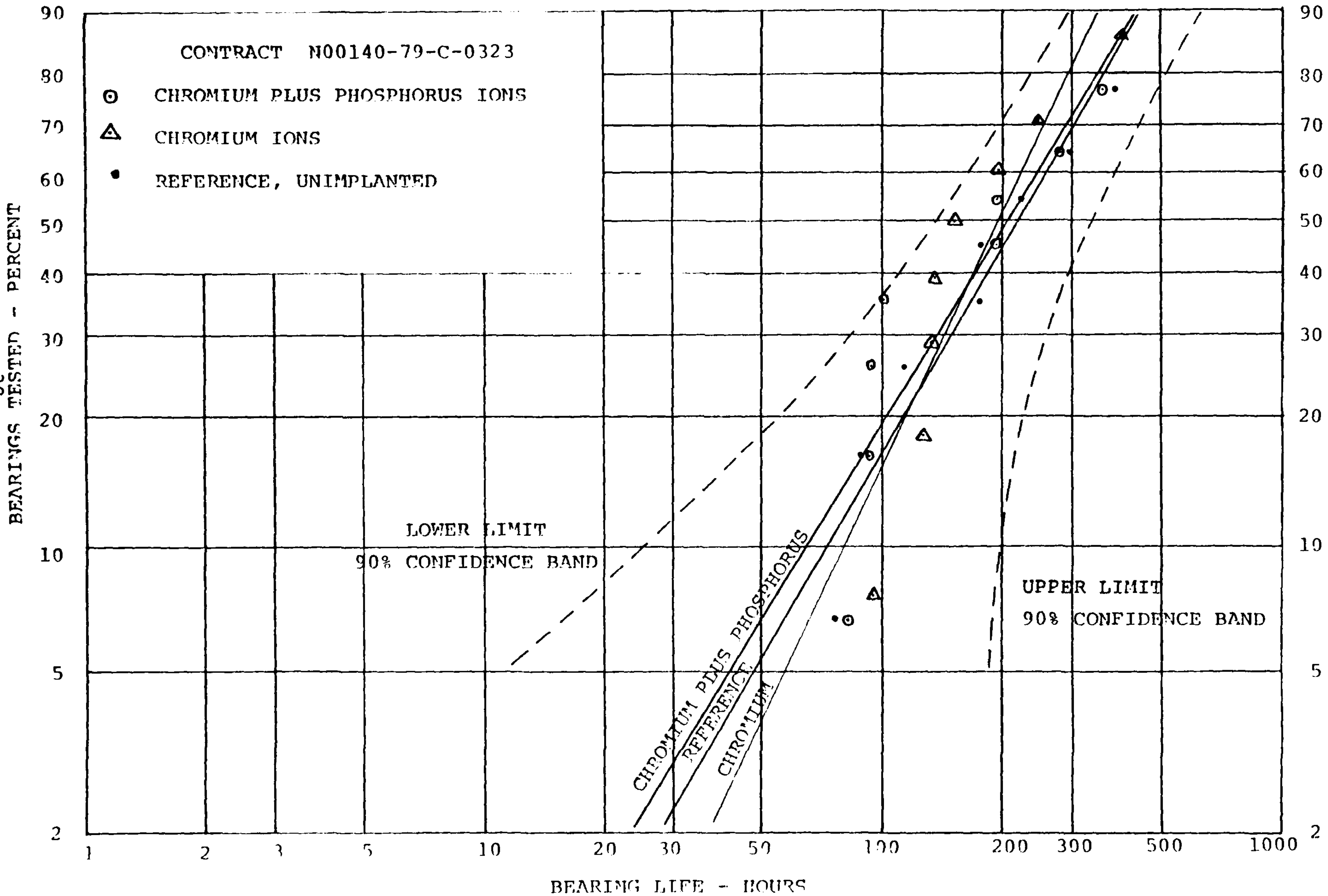


FIGURE 8 - CIRCUMFERENTIAL PROFILE TRACE OF TYPICAL ROLLER

(THIS ROLLER WAS ION IMPLANTED AND HAD DISTINCT DISCOLORED BAND)

FIGURE 9 - FATIGUE ENDURANCE OF ION IMPLANTED ROLLER BEARINGS



BEFORE IMPLANTATION

AFTER IMPLANTATION

AFTER TEST

FIGURE 10 - SEM PHOTOS OF INNER RACE OF S/N R8.
RACEWAY WAS IMPLANTED WITH CHROMIUM
PLUS PHOSPHORUS. MAGNIFICATION 4700X

AFTER IMPLANTATION

AFTER TEST

FIGURE 11 - SEM PHOTOS OF INNER RACE OF S/N R18.
RACEWAY WAS IMPLANTED WITH CHROMIUM IONS
MAGNIFICATION 4700X

[illegible]

AFTER IMPLANTATION

AFTER TEST

[illegible] - [illegible] PHOTOS OF REPLICAS OF OUTER RACE OF S/N E8.
[illegible] WAS IMPLANTED WITH CHROMIUM PLUS PHOSPHORUS
[illegible] 4700X

A) AFTER IMPLANTATION

B) AFTER TEST

FIGURE 13 - SEM PHOTOS OF REPLICAS OF OUTER RACE OF S/N R18, SHOWING GRINDING FURROW NEAR CENTER OF RACE, MOTTLED APPEARANCE ON PHOTOGRAPH "A" DUE TO FOREIGN MATERIAL. RACEWAY WAS IMPLANTED WITH CHROMIUM IONS. MAGNIFICATION 4700X


001.0 u
05-3 20.0 6 007 052


001.0 u
05-3 20.0 27 421 007


001.0 u
05-3 20.0 21 623 038

FIGURE 15

RESIDUAL STRESS MEASUREMENTS

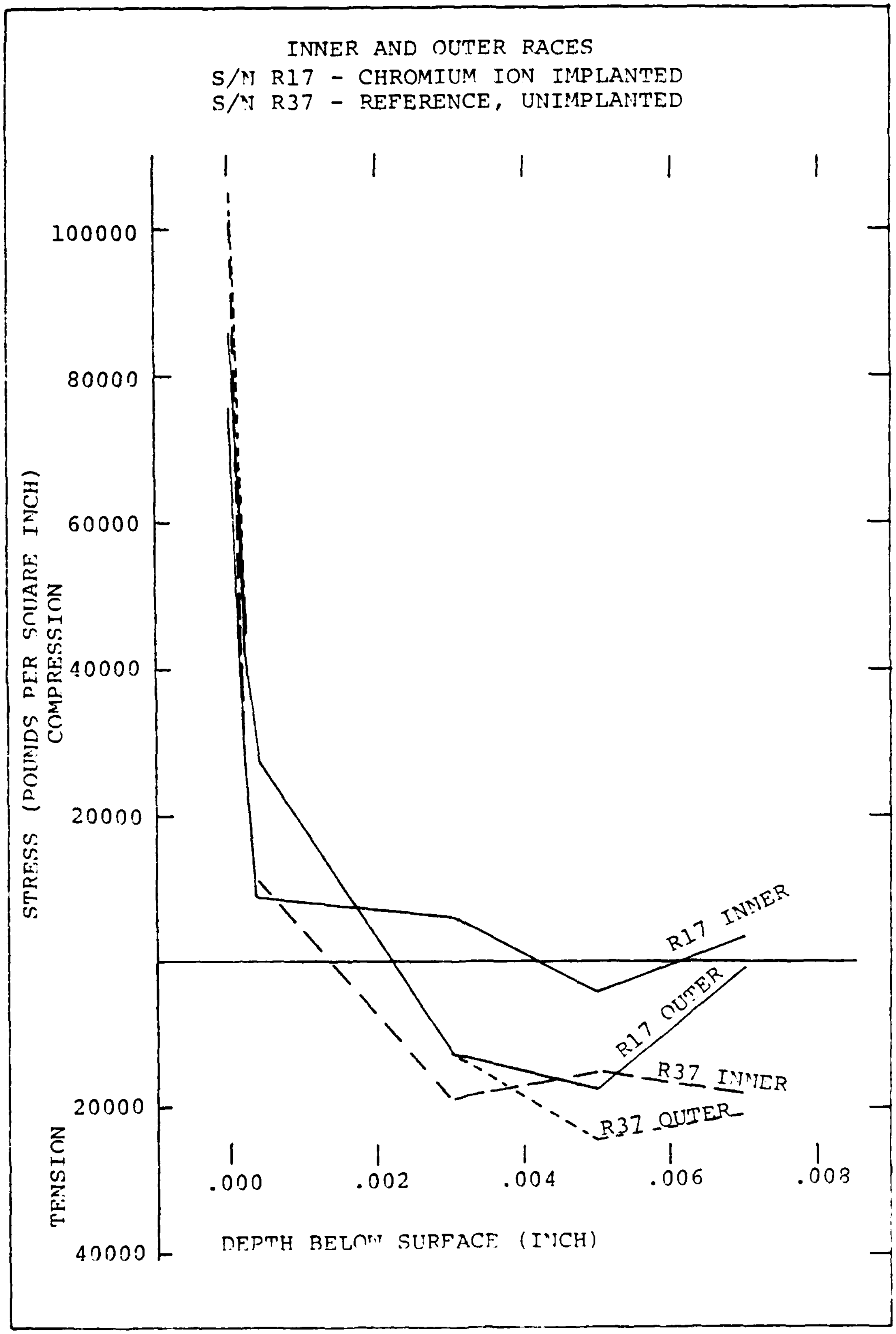
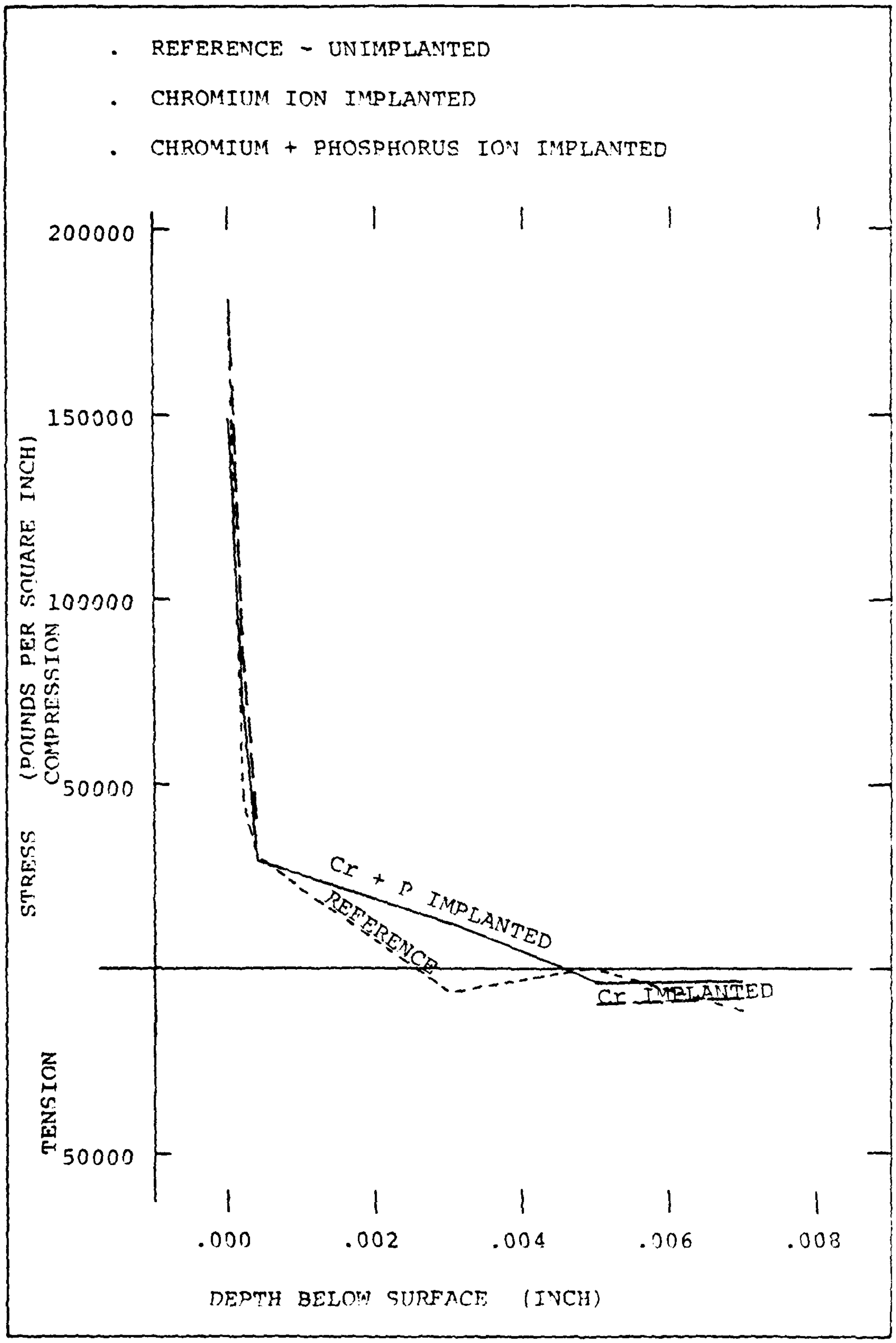
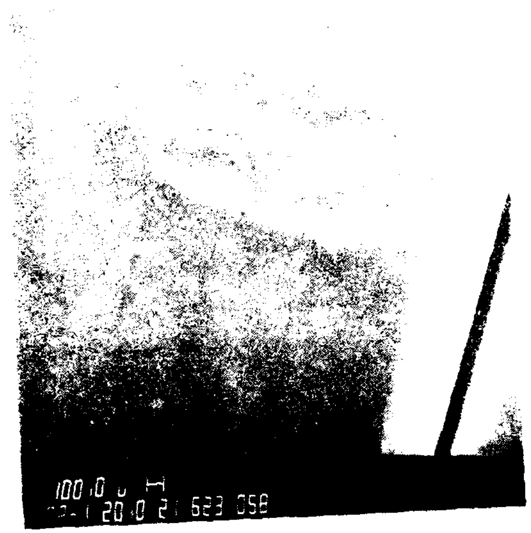


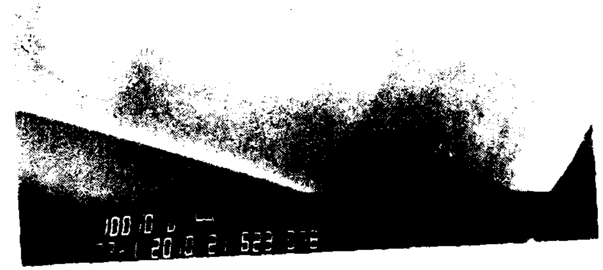
FIGURE 16

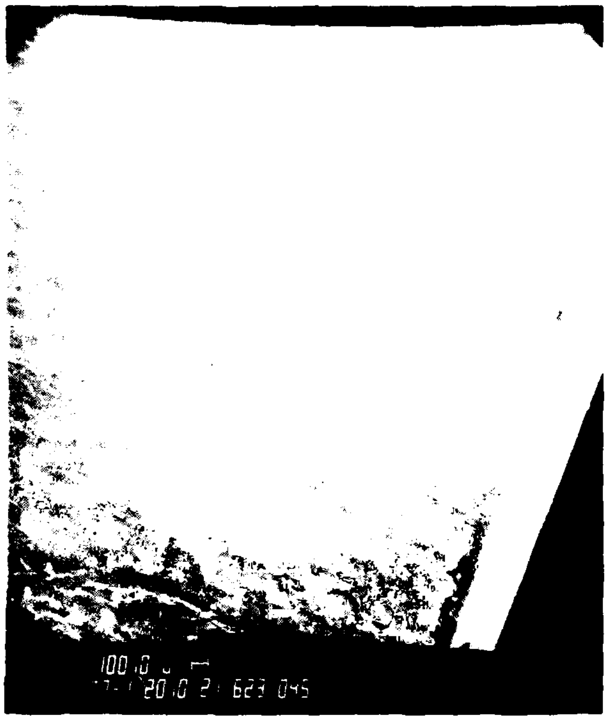
RESIDUAL STRESS MEASUREMENTS 7x7mm ROLLERS




100.0 µ
20.0 21 623 056


100.0 µ
20.0 21 623 058

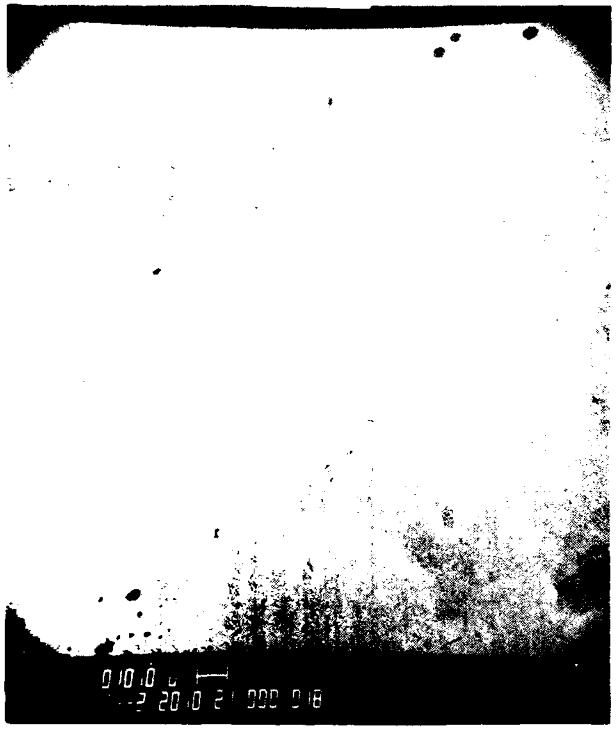


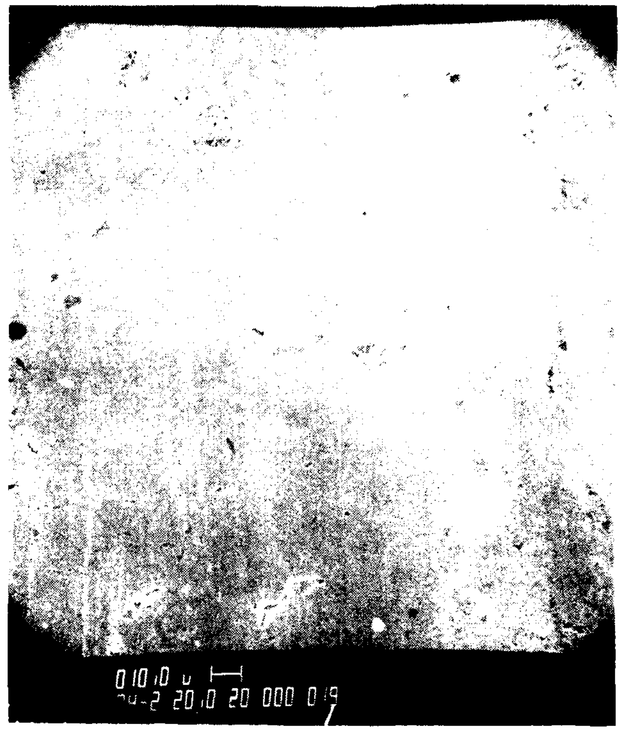

100.0
623 045

CORNER

CORNER

FIGURE 19 - SEM PHOTOS OF AREA ADJACENT TO CORNERS ON A ROLLER FROM S/N R7. MAGNIFICATION 400X. THIS BEARING RAN 420 HOURS WITHOUT FAILURE BUT ROLLERS WERE HIGHLY BURNISHED NEAR CORNERS.





CORNER CORNER

FIGURE 29 - SEM PHOTOS OF AREA ADJACENT TO CORNERS ON TYPICAL ROLLER WHICH DID NOT FAIL. MAGNIFICATION 400X. ROLLER WAS CHROMIUM ION IMPLANTED AND USED IN S/N R16.

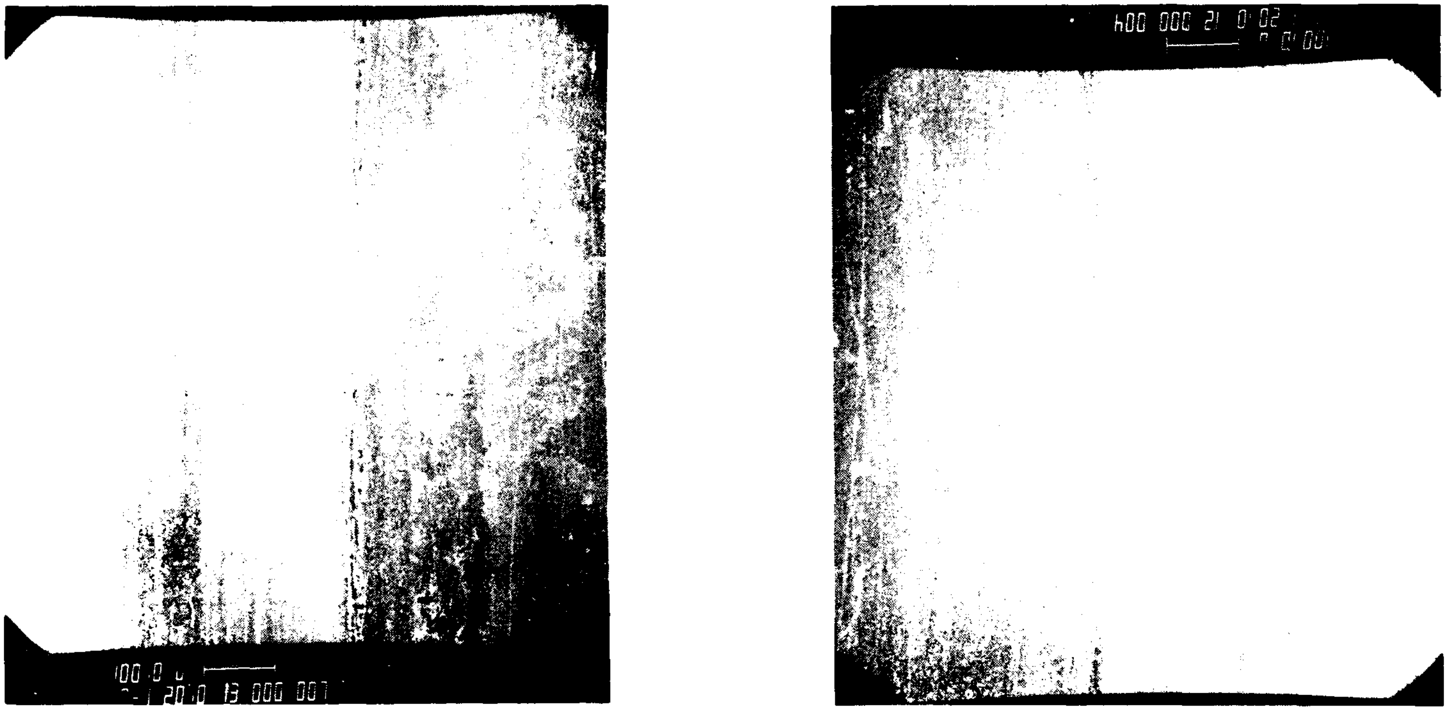
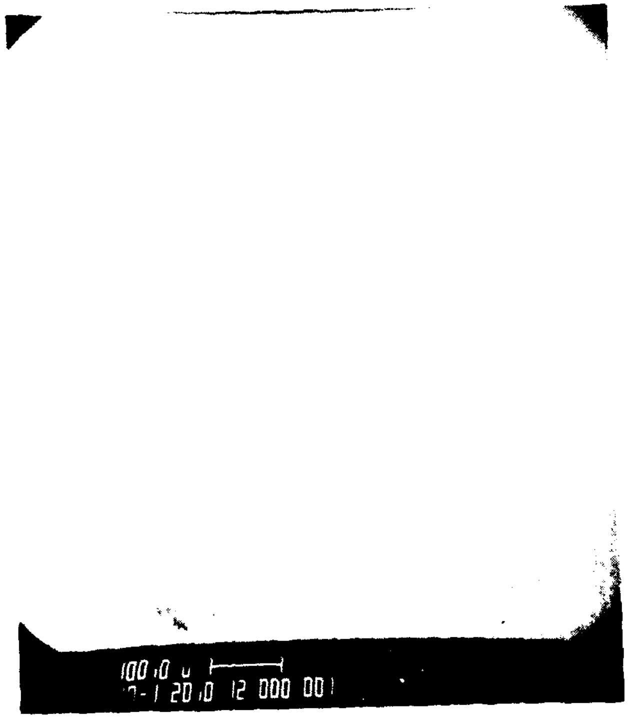


FIGURE 21 - SEM PHOTOS OF INNER RACEWAY [illegible] E7. MAGNIFICATION 100X. WHITE AREAS [illegible] RING FLANGES WHICH ARE OUT OF FOCUS. [illegible] BEARING WERE BURNISHED ON BOTH [illegible].



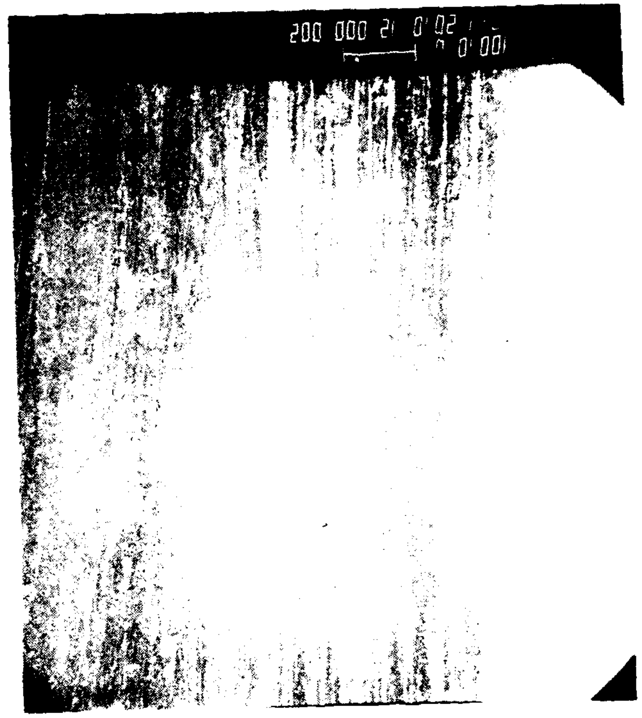
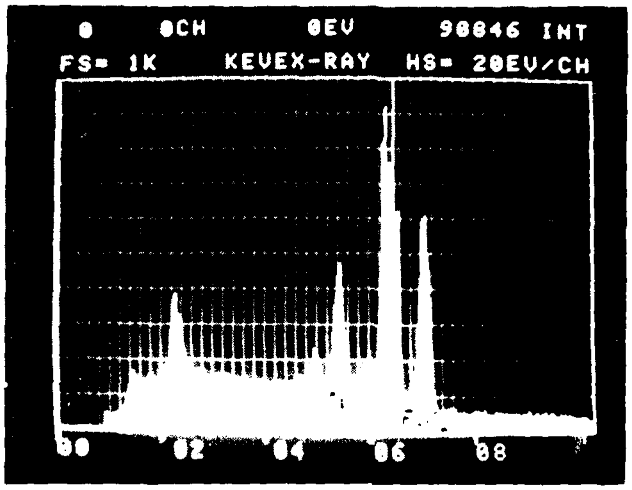
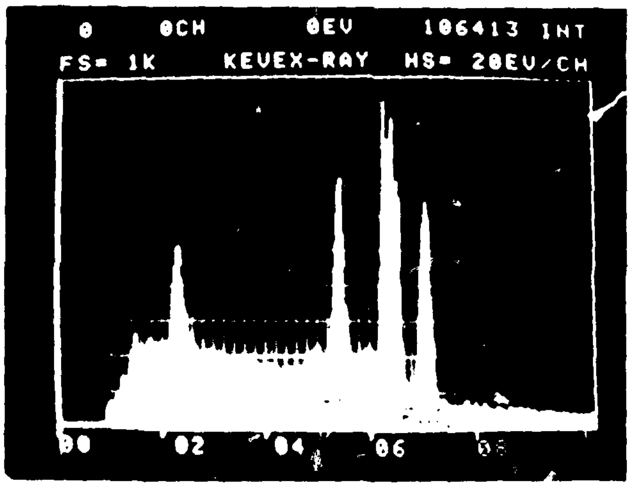


FIGURE 22 - [illegible]
MAGNIFICATION [illegible] WHICH [illegible]
APPROXIMATELY [illegible] INCH FROM [illegible].

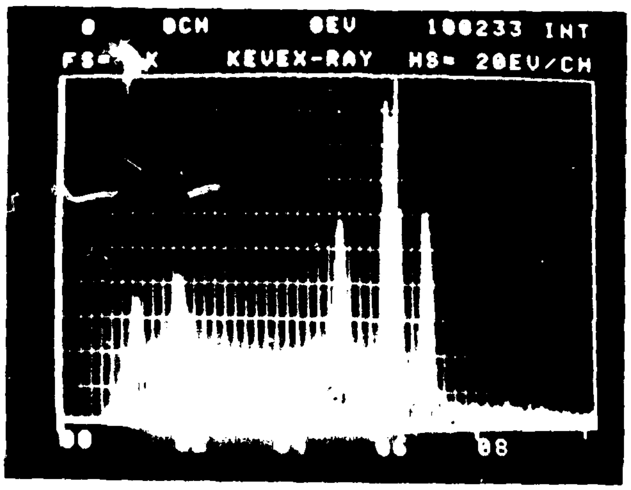
NO IMPLANTATION



AS IMPLANTED

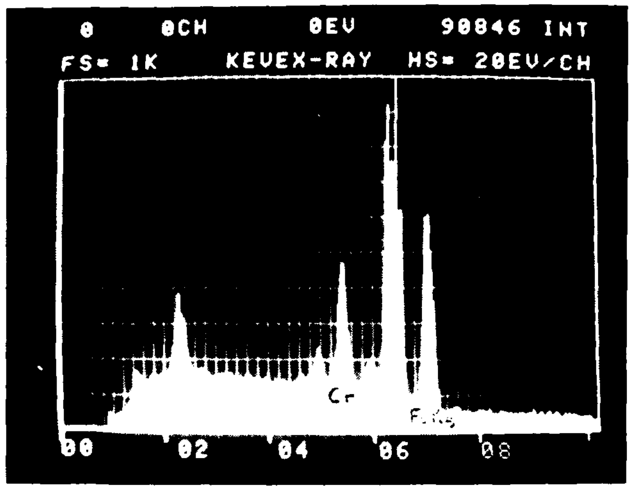


ROLLER USED IN
S/N R20

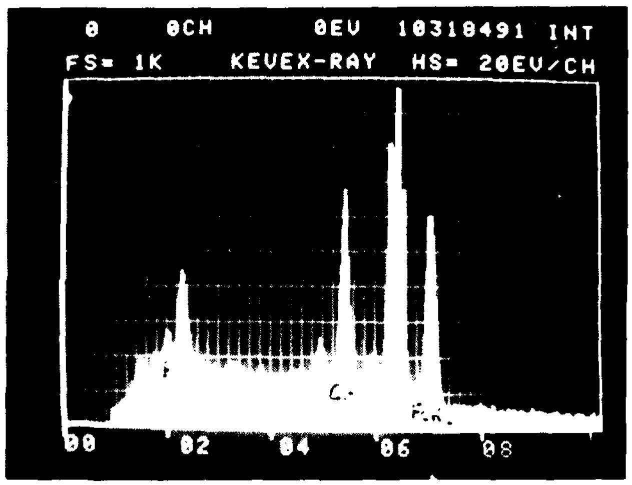


[illegible]

NO IMPLANTATION



AS IMPLANTED



ROLLER USED IN
S/N R7

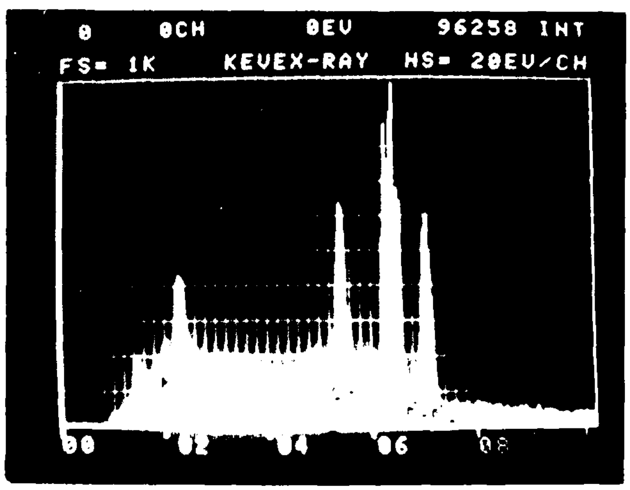
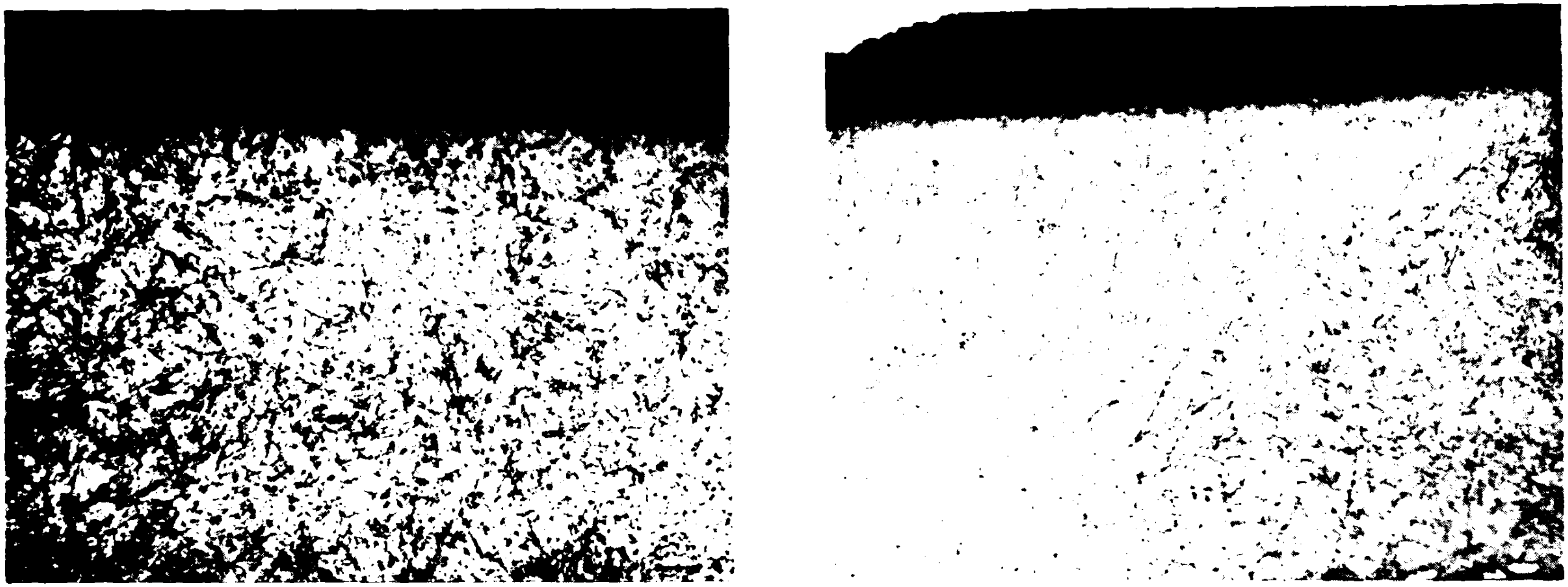


FIGURE 24 - SURFACE [illegible]
CHROMIUM [illegible]



a) INNER RACE FROM S/N 827, UNIMPLANTED

b) OUTER RACE FROM S/N 838, CHROMIUM ION IMPLANTED

FIGURE 25 - COMPARISON OF MICROSTRUCTURE OF IMPLANTED AND UNIMPLANTED PARTS

[illegible] X

```
                    ROLLING ELEMENT BEARING ANALYSIS PROGRAM  (5 DEGREES OF FREEDOM)

ROLLER BEARING ANALYSIS - R108KD7 - RESEARCH

INPUT DATA FOR INDIVIDUAL BEARINGS

 BEARING   TYPE OF   NUMBER OF  ELEMENT     PITCH       CONTACT     RACE CURVATURES      DIAMETRAL    BEARING
   NO.     BEARING   ELEMENTS   DIAMETER    DIAMETER    ANGLE       OUTER       INNER    CLEARANCE    LOCATION
    1       CYLN       18       2.7620E-01  2.1260E 00  0.0         0.0         0.0      1.5000E-03   0.0

 BEARING  ROLL LENGTH  MODULUS OF ELASTICITY    POISSONS RATIO         FATIGUE CONSTANT        VALUES OF LAMBDA
   NO.    (EFFECTIVE)  RACES      ELEMENTS      RACES       ELEMENTS   OUTER       INNER       OUTER       INNER
    1     2.4060E-01   2.9000E 07 2.9000E 07    2.5000E-01  2.5000E-01 4.9500E 04  4.9500E 04  6.6000E-01  6.6000E-01

 BEARING          INITIAL DISPLACEMENTS AT BEARING CENTER            AXIAL       PRELOAD     PRELOAD       PHASE
   NO.     ALONG X     ALONG Y     ALONG Z     ABOUT X     ABOUT Y   PRELOAD     DEFLECTION  CONTACT ANG.  ANGLE
    1      0.0         0.0         0.0         0.0         0.0       0.0         0.0         0.0           0.0

 BEARING   WEIBULL     LOAD-LIFE   AXIAL       RADIAL      ETA       CONE RIB    SHOULDER CLEARANCE    SHOULDER
   NO.     SLOPE       EXPONENT    FLOAT       FLOAT       (DEG)     DIA.(IN)    INBOARD (IN) OUTBOARD HEIGHT(IN)
    1      1.1250E 00  3.3333E 00  NO          NO          0.0       0.0         0.0          0.0      0.0

 BEARING   CAGE        AXIAL SPRING  ROLL CYLN.  CROWN       BALL          LIFE ADJUSTMENT FACTORS
   NO.     OPENING                   LENGTH                  EXP.      RELIABILITY  MATERIAL    LUBRICATION
    1      0.0         NO            9.2000E-02  3.0270E 01  0.0       1.0000E 00   1.0000E 00  1.0000E 00

   ROW    1 HAS   18 ELEMENTS AND WAS MODELED WITH    18 ELEMENTS

INPUT DATA FOR BEARING SYSTEM
                     EXTERNAL FORCES AND MOMENTS APPLIED TO SHAFT
    RPM        ALONG X      ALONG Y     ALONG Z     ABOUT X     ABOUT Y
 (RELATIVE)      F1           F2          F3          F4          F5
 7.0000E 03  -2.8600E 03    0.0         0.0         0.0         0.0

INNER RACES ROTATE WITH RESPECT TO LOAD
OUTER  RACES STATIONARY WITH RESPECT TO LOAD
PROBLEM IS POSED IN FOLLOWING DEGREES OF FREEDOM
ALONGX,
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OUTPUT DATA FOR BEARING SYSTEM     NUMBER OF ITERATIONS =  3

**** LIFE COMPUTED PER AFBMA STANDARDS ****

HOURS LIFE             SYSTEM REACTIONS ON SHAFT AT ORIGIN
  (H-10)     ALONG X     ALONG Y     ALONG Z     ABOUT X     ABOUT Y
1.4433F 01  2.8600E 03  1.6174E-03  0.0         2.1370E-06  5.9709E-05

                    DISPLACEMENTS OF REFERENCE LINE AT ORIGIN
             ALONG X     ALONG Y     ALONG Z     ABOUT X     ABOUT Y
            -2.0169E-03  0.0         0.0         0.0         0.0

                                          NON-LINEAR SPRING RATES OF SYSTEM AT ORIGIN
             DFX/DX      DFX/DY      DFX/DZ      DFX/DALX    DFX/DALY    DFY/DY      DFY/DZ      DFY/DALX    DFY/DALY
            -3.1452E 06  0.0         0.0         0.0         0.0         0.0         0.0         0.0         0.0

                                                 NON-LINEAR SPRING RATES (CONTINUED)
             DFZ/DZ      DFZ/DALX    DFZ/DALY    DMX/DALX    DMX/DALY    DMY/DALY
             0.0         0.0         0.0         0.0         0.0         0.0

 BEARING                  REACTIONS OF BEARINGS ON SHAFT                          (B-10)
   NO.       ALONG X     ALONG Y     ALONG Z     ABOUT X     ABOUT Y               LIFE
    1       2.8600E 03  1.6174E-03  0.0         2.1370E-06  5.9709E-05         1.4433E 01

 BEARING            RELATIVE SHAFT DISPLACEMENTS AT BEARING CENTER
   NO.       ALONG X     ALONG Y     ALONG Z     ABOUT X     ABOUT Y               CAPACITY                EQIV. LOAD
    1       -2.0169E-03  0.0         0.0         0.0         0.0                 5.6875E 03   (RADIAL)   3.3124E 03


 BEARING              PARTIAL DERIVATIVES OF BEARING REACTIONS WITH RESPECT TO DISPLACEMENTS AT SYSTEM ORIGIN
   NO.       DFX/DX      DFX/DY      DFX/DZ      DFX/DALX    DFX/DALY    DFY/DY      DFY/DZ      DFY/DALX    DFY/DALY
    1       -3.1452E 06  0.0         0.0         0.0         0.0         0.0         0.0         0.0         0.0

 BEARING                                         PARTIAL DERIVATIVES   (CONTINUED)
   NO.       DFZ/DZ      DFZ/DALX    DFZ/DALY    DMX/DALX    DMX/DALY    DMY/DALY
    1        0.0         0.0         0.0         0.0         0.0         0.0
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APPENDIX A-1 - PAGE 3

CYLN. ROLLER BEARING OUTPUT DATA FOR ROW NUMBER 1

ROLL NO.	LOCATION ANGLE (DEG)	ROLLER LOAD OUTER (LBS)	ROLLER LOAD INNER (LBS)	CONE RIB LOAD (LBS)	MOMENT ON ROLL (IN-LBS)	ROLL EFFECTIVE LENGTH OUTER (IN)	ROLL EFFECTIVE LENGTH INNER (IN)	ROLL DEFL. (IN)	ROLL TILT (RAD.)	MAXIMUM STRESS (PSI)	LAMINA LOADING
1	2.000E 01	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	00000000000000000000
2	4.000E 01	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	00000000000000000000
3	6.000E 01	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	00000000000000000000
4	8.000E 01	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	00000000000000000000
5	1.000E 02	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	00000000000000000000
6	1.200E 02	9.433E 01	9.433E 01	0.0	2.980E-06	1.925E-01	1.925E-01	1.292E-04	0.0	1.263E 05	00111112222222211111100
7	1.400E 02	4.403E 02	4.403E 02	0.0	2.861E-06	2.406E-01	2.406E-01	3.975E-04	1.054E-10	2.328E 05	11111122222222111111
8	1.600E 02	6.947E 02	6.947E 02	0.0	4.959E-05	2.406E-01	2.406E-01	5.726E-04	1.987E-15	2.851E 05	11111122222222111111
9	1.800E 02	7.855E 02	7.855E 02	0.0	7.534E-05	2.406E-01	2.406E-01	6.335E-04	0.0	3.016E 05	11111122222222111111
10	2.000E 02	6.947E 02	6.947E 02	0.0	6.008E-05	2.406E-01	2.406E-01	5.726E-04	1.818E-15	2.851E 05	11111122222222111111
11	2.200E 02	4.403E 02	4.403E 02	0.0	2.861E-06	2.406E-01	2.406E-01	3.975E-04	1.159E-10	2.328E 05	11111122222222111111
12	2.400E 02	9.433E 01	9.433E 01	0.0	4.232E-06	1.925E-01	1.925E-01	1.292E-04	0.0	1.263E 05	00111112222222211111100
13	2.600E 02	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	00000000000000000000
14	2.800E 02	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	00000000000000000000
15	3.000E 02	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	00000000000000000000
16	3.200E 02	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	00000000000000000000
17	3.400E 02	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	00000000000000000000
18	3.600E 02	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	00000000000000000000

INDIVIDUAL ROLLER DATA

ROW	1
ROLLER	9
LOCATION ANGLE(DEG)	1.80000E 02
LAMINA WIDTH(IN)	1.20300E-02
EFFECTIVE LENGTH(OUTER)(IN)	2.40600E-01
EFFECTIVE LENGTH(INNER)(IN)	2.40600E-01
CONE RIB FORCE(LBS)	0.0
ROLLER HALF ANGLE (DEG)	0.0

LAMINA NUMBER	DISTANCE TO ROLL CENTER (IN)	LAMINA UNIT LOAD (LB/IN) OUTER	INNER	HERTZ CONTACT STRESS (MEAN PSI) OUTER	INNER	CONTACT SEMI WIDTH OUTER	INNER	SUBSURFACE SHEAR (INNER) STRESS (PSI)	DEPTH (IN)
1	-1.1428E-01	2.4772E 03	2.4772E 03	2.1957E 05	2.5022E 05	5.6410E-03	4.9501E-03	9.5655E 04	3.8913E-03
2	-1.0225E-01	2.7402E 03	2.7402E 03	2.3093E 05	2.6316E 05	5.9329E-03	5.2062E-03	1.0060E 05	4.0926E-03
3	-9.0225E-02	2.9761E 03	2.9761E 03	2.4067E 05	2.7426E 05	6.1830E-03	5.4257E-03	1.0485E 05	4.2651E-03
4	-7.8195E-02	3.1841E 03	3.1841E 03	2.4893E 05	2.8368E 05	6.3954E-03	5.6121E-03	1.0845E 05	4.4117E-03
5	-6.6165E-02	3.3634E 03	3.3634E 03	2.5585E 05	2.9156E 05	6.5730E-03	5.7680E-03	1.1146E 05	4.5342E-03
6	-5.4135E-02	3.5136E 03	3.5136E 03	2.6150E 05	2.9800E 05	6.7182E-03	5.8954E-03	1.1392E 05	4.6343E-03
7	-4.2105E-02	3.5984E 03	3.5984E 03	2.6464E 05	3.0157E 05	6.7988E-03	5.9661E-03	1.1529E 05	4.6900E-03
8	-3.0075E-02	3.5984E 03	3.5984E 03	2.6464E 05	3.0157E 05	6.7988E-03	5.9661E-03	1.1529E 05	4.6900E-03
9	-1.8045E-02	3.5984E 03	3.5984E 03	2.6464E 05	3.0157E 05	6.7988E-03	5.9661E-03	1.1529E 05	4.6900E-03
10	-6.0150E-03	3.5984E 03	3.5984E 03	2.6464E 05	3.0157E 05	6.7988E-03	5.9661E-03	1.1529E 05	4.6900E-03
11	6.0150E-03	3.5984E 03	3.5984E 03	2.6464E 05	3.0157E 05	6.7988E-03	5.9661E-03	1.1529E 05	4.6900E-03
12	1.8045E-02	3.5984E 03	3.5984E 03	2.6464E 05	3.0157E 05	6.7988E-03	5.9661E-03	1.1529E 05	4.6900E-03
13	3.0075E-02	3.5984E 03	3.5984E 03	2.6464E 05	3.0157E 05	6.7988E-03	5.9661E-03	1.1529E 05	4.6900E-03
14	4.2105E-02	3.5984E 03	3.5984E 03	2.6464E 05	3.0157E 05	6.7988E-03	5.9661E-03	1.1529E 05	4.6900E-03
15	5.4135E-02	3.5136E 03	3.5136E 03	2.6150E 05	2.9800E 05	6.7182E-03	5.8954E-03	1.1392E 05	4.6343E-03
16	6.6165E-02	3.3634E 03	3.3634E 03	2.5585E 05	2.9156E 05	6.5730E-03	5.7680E-03	1.1146E 05	4.5342E-03
17	7.8195E-02	3.1841E 03	3.1841E 03	2.4893E 05	2.8368E 05	6.3954E-03	5.6121E-03	1.0845E 05	4.4117E-03
18	9.0225E-02	2.9761E 03	2.9761E 03	2.4067E 05	2.7426E 05	6.1830E-03	5.4257E-03	1.0485E 05	4.2651E-03
19	1.0225E-01	2.7402E 03	2.7402E 03	2.3093E 05	2.6316E 05	5.9329E-03	5.2062E-03	1.0060E 05	4.0926E-03
20	1.1428E-01	2.4772E 03	2.4772E 03	2.1957E 05	2.5022E 05	5.6410E-03	4.9501E-03	9.5655E 04	3.8913E-03

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                    ROLLING ELEMENT BEARING ANALYSIS PROGRAM  (5 DEGREES OF FREEDOM)

ROLLER BEARING ANALYSIS - R108KD7 - RESEARCH

INPUT DATA FOR INDIVIDUAL BEARINGS

 BEARING   TYPE OF    NUMBER OF   ELEMENT     PITCH        CONTACT      RACE CURVATURES         DIAMETRAL   BEARING
   NO.     BEARING    ELEMENTS    DIAMETER    DIAMETER      ANGLE       OUTER      INNER        CLEARANCE   LOCATION
    1       CYLN        18        2.7620E-01  2.1260E 00   0.0          0.0        0.0          1.5000E-03  0.0

 BEARING  ROLL LENGTH  MODULUS OF ELASTICITY      POISSONS RATIO        FATIGUE CONSTANT           VALUES OF LAMBDA
   NO.    (EFFECTIVE)   RACES      ELEMENTS      RACES       ELEMENTS    OUTER       INNER         OUTER       INNER
    1     2.4060E-01  2.9000E 07  2.9000E 07  2.5000E-01  2.5000E-01  4.9500E 04  4.9500E 04  6.6000E-01  6.6000E-01

 BEARING              INITIAL DISPLACEMENTS AT BEARING CENTER                AXIAL      PRELOAD     PRELOAD       PHASE
   NO.     ALONG X     ALONG Y     ALONG Z     ABOUT X     ABOUT Y        PRELOAD   DEFLECTION  CONTACT ANG.   ANGLE
    1      0.0         0.0         0.0         0.0         0.0            0.0       0.0         0.0           0.0

 BEARING   WEIBULL    LOAD-LIFE    AXIAL       RADIAL        ETA        CONE RIB   SHOULDER CLEARANCE      SHOULDER
   NO.      SLOPE     EXPONENT     FLOAT       FLOAT        (DEG)       DIA.(IN)  INBOARD (IN) OUTBOARD    HEIGHT(IN)
    1     1.1250E 00  3.3333E 00    NO          NO         0.0        0.0         0.0         0.0          0.0

 BEARING     CAGE     AXIAL SPRING  ROLL CYLN.  CROWN       BALL              LIFE ADJUSTMENT FACTORS
   NO.      OPENING                 LENGTH                  EXP.       RELIABILITY  MATERIAL    LUBRICATION
    1       0.0          NO         1.7200E-01  3.0270E 01  0.0        1.0000E 00  1.0000E 00  1.0000E 00

   ROW    1 HAS   18 ELEMENTS AND WAS MODELED WITH    18 ELEMENTS

INPUT DATA FOR BEARING SYSTEM

                  EXTERNAL FORCES AND MOMENTS APPLIED TO SHAFT
   RPM        ALONG X     ALONG Y     ALONG Z     ABOUT X     ABOUT Y
(RELATIVE)      F1          F2          F3          F4          F5
 7.0000E 03 -2.8600E 03  0.0         0.0         0.0         0.0

INNER RACES ROTATE WITH RESPECT TO LOAD
OUTER  RACES STATIONARY WITH RESPECT TO LOAD
PROBLEM IS POSED IN FOLLOWING DEGREES OF FREEDOM
ALONGX,
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CYLN. ROLLER BEARING OUTPUT DATA FOR ROW NUMBER 1

ROLL NO.	LOCATION ANGLE (DEG)	ROLLER LOAD OUTER (LBS)	ROLLER LOAD INNER (LBS)	CONE RIB LOAD (LBS)	MOMENT ON ROLL (IN-LBS)	ROLL EFFECTIVE LENGTH OUTER (IN)	ROLL EFFECTIVE LENGTH INNER (IN)	ROLL DEFL. (IN)	ROLL TILT (RAD.)	MAXIMUM STRESS (PSI)	LAMINA LOADING
1	2.000E 01	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	00000000000000000000
2	4.000E 01	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	00000000000000000000
3	6.000E 01	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	00000000000000000000
4	8.000E 01	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	00000000000000000000
5	1.000E 02	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	00000000000000000000
6	1.200E 02	1.025E 02	1.025E 02	0.0	5.960E-06	2.406E-01	2.406E-01	1.078E-04	0.0	1.127E 05	11122222222222222111
7	1.400E 02	4.467E 02	4.467E 02	0.0	3.815E-06	2.406E-01	2.406E-01	3.647E-04	5.192E-11	2.219E 05	11122222222222222111
8	1.600E 02	6.905E 02	6.905E 02	0.0	6.104E-05	2.406E-01	2.406E-01	5.323E-04	0.0	2.738E 05	11122222222222222111
9	1.800E 02	7.775E 02	7.775E 02	0.0	8.869E-05	2.406E-01	2.406E-01	5.905E-04	0.0	2.900E 05	11122222222222222111
10	2.000E 02	6.905E 02	6.905E 02	0.0	6.294E-05	2.406E-01	2.406E-01	5.323E-04	0.0	2.738E 05	11122222222222222111
11	2.200E 02	4.467E 02	4.467E 02	0.0	2.861E-06	2.406E-01	2.406E-01	3.647E-04	0.0	2.219E 05	11122222222222222111
12	2.400E 02	1.025E 02	1.025E 02	0.0	5.662E-06	2.406E-01	2.406E-01	1.078E-04	0.0	1.127E 05	11122222222222222111
13	2.600E 02	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	00000000000000000000
14	2.800E 02	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	00000000000000000000
15	3.000E 02	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	00000000000000000000
16	3.200E 02	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	00000000000000000000
17	3.400E 02	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	00000000000000000000
18	3.600E 02	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	00000000000000000000

INDIVIDUAL ROLLER DATA

ROW 1
ROLLER 9
LOCATION ANGLE(DEG) 1.80000E 02
LAMINA WIDTH(IN) 1.20300E-02
EFFECTIVE LENGTH(OUTER)(IN) 2.40600E-01
EFFECTIVE LENGTH(INNER)(IN) 2.40600E-01
CONE RIB FORCE(LBS) 0.0
ROLLER HALF ANGLE (DEG) 0.0

LAMINA NUMBER	DISTANCE TO ROLL CENTER (IN)	LAMINA UNIT LOAD OUTER (LB/IN)	INNER	HERTZ CONTACT STRESS OUTER (MEAN PSI)	INNER	CONTACT SEMI WIDTH OUTER	INNER	SUBSURFACE SHEAR (INNER) STRESS (PSI)	DEPTH (IN)
1	-1.1428E-01	2.7480E 03	2.7480E 03	2.3126E 05	2.6354E 05	5.9414E-03	5.2137E-03	1.0075E 05	4.0985E-03
2	-1.0225E-01	3.0136E 03	3.0136E 03	2.4218E 05	2.7598E 05	6.2219E-03	5.4598E-03	1.0551E 05	4.2920E-03
3	-9.0225E-02	3.2517E 03	3.2517E 03	2.5156E 05	2.8668E 05	6.4630E-03	5.6714E-03	1.0959E 05	4.4583E-03
4	-7.8195E-02	3.3286E 03	3.3286E 03	2.5452E 05	2.9005E 05	6.5390E-03	5.7381E-03	1.1088E 05	4.5107E-03
5	-6.6165E-02	3.3286E 03	3.3286E 03	2.5452E 05	2.9005E 05	6.5390E-03	5.7381E-03	1.1088E 05	4.5107E-03
6	-5.4135E-02	3.3286E 03	3.3286E 03	2.5452E 05	2.9005E 05	6.5390E-03	5.7381E-03	1.1088E 05	4.5107E-03
7	-4.2105E-02	3.3286E 03	3.3286E 03	2.5452E 05	2.9005E 05	6.5390E-03	5.7381E-03	1.1088E 05	4.5107E-03
8	-3.0075E-02	3.3286E 03	3.3286E 03	2.5452E 05	2.9005E 05	6.5390E-03	5.7381E-03	1.1088E 05	4.5107E-03
9	-1.8045E-02	3.3286E 03	3.3286E 03	2.5452E 05	2.9005E 05	6.5390E-03	5.7381E-03	1.1088E 05	4.5107E-03
10	-6.0150E-03	3.3286E 03	3.3286E 03	2.5452E 05	2.9005E 05	6.5390E-03	5.7381E-03	1.1088E 05	4.5107E-03
11	6.0150E-03	3.3286E 03	3.3286E 03	2.5452E 05	2.9005E 05	6.5390E-03	5.7381E-03	1.1088E 05	4.5107E-03
12	1.8045E-02	3.3286E 03	3.3286E 03	2.5452E 05	2.9005E 05	6.5390E-03	5.7381E-03	1.1088E 05	4.5107E-03
13	3.0075E-02	3.3286E 03	3.3286E 03	2.5452E 05	2.9005E 05	6.5390E-03	5.7381E-03	1.1088E 05	4.5107E-03
14	4.2105E-02	3.3286E 03	3.3286E 03	2.5452E 05	2.9005E 05	6.5390E-03	5.7381E-03	1.1088E 05	4.5107E-03
15	5.4135E-02	3.3286E 03	3.3286E 03	2.5452E 05	2.9005E 05	6.5390E-03	5.7381E-03	1.1088E 05	4.5107E-03
16	6.6165E-02	3.3286E 03	3.3286E 03	2.5452E 05	2.9005E 05	6.5390E-03	5.7381E-03	1.1088E 05	4.5107E-03
17	7.8195E-02	3.3286E 03	3.3286E 03	2.5452E 05	2.9005E 05	6.5390E-03	5.7381E-03	1.1088E 05	4.5107E-03
18	9.0225E-02	3.2517E 03	3.2517E 03	2.5156E 05	2.8668E 05	6.4630E-03	5.6714E-03	1.0959E 05	4.4583E-03
19	1.0225E-01	3.0136E 03	3.0136E 03	2.4218E 05	2.7598E 05	6.2219E-03	5.4598E-03	1.0551E 05	4.2920E-03
20	1.1428E-01	2.7480E 03	2.7480E 03	2.3126E 05	2.6354E 05	5.9414E-03	5.2137E-03	1.0075E 05	4.0985E-03

DATE
FILMED
8